Effect of amplitude envelope on detectability of warning sound for quiet vehicle

Nozomiko YASUI[1]; Masanobu MIURA[2]

[1] National Institute of Technology, Matsue College, Japan

[2] Faculty of Science and Technology, Ryukoku University, Japan

ABSTRACT

The motor sound on quiet vehicle, such as hybrid and electric vehicle, is quiet at low speeds. Thus, pedestrians have difficulty recognizing quiet vehicles approaching them. A quiet vehicle was designed to play a warning sound to solve this problem. However, it has not been solved yet. When the sound is designed, it should be concerned not only detectability of approaching quiet vehicles but also impression of the sound. For pedestrians, it's important to make it easier to recognize quiet vehicle. Also, warning sounds should not contribute to traffic noise annoyance. Our previous studies found that the fluctuation frequency and non-periodic fluctuation are effective to enable people to notice approaching vehicles. Another studies showed that the shape of envelope and the frequency contribute to impression of warning sound. This paper describes the unclear points of previous, say, the effect of the envelope on detectability of warning sound. Investigations were carried out by using synthesized motor sounds which were designed to have periodic and non-periodic fluctuations, and their effects on detectability by pedestrians were assessed. The results revealed that the shape of envelope influences the ability with which people detect approaching quiet vehicles in case of slow fluctuation frequency.

Keywords: Quiet vehicle, Detectability, Envelope I-INCE Classification of Subjects Number(s): 11.9.9, 63.7

1. INTRODUCTION

Quiet vehicles(QVs), such as hybrid(HVs) or electric vehicles(EVs) are comparatively quieter than gasoline powered vehicles, especially when they are driven at low speeds. The motors equipped on quiet vehicles are designed to provide calm environments to drivers. However, pedestrians have trouble recognizing their approach in an urban sound environment because they are too quiet. According to the report of the National Highway Traffic Safety Administration (NHTSA), United States(1), QVs are nearly twice as likely as gasoline powered vehicles to be involved in accidents involving pedestrians. This is of particular concern to the blind community. The National Federation of the Blind and the World Blind Union have expressed their concerns and requested the development of a regulation requiring automobiles to emit a minimum level of sound to alert blind and other pedestrians(2).

To solve these problems, new regulations and recommendations are currently being studied in various governments. The Japanese government published guideline for Measures on the Quietness of Hybrid Electric Vehicles in February 2010(3). The guideline states that a warning sound should be automatically emitted when the vehicle is driven at a speed of less than 20 km/h, the sound should be continuous and evoke the running condition of a vehicle, and its sound level should not exceed that of a gasoline powered vehicle running at a speed of 20 km/h. The Quiet Road Transport Vehicles (QRTV) Work Group, which was established by UN/ECE/WP.29/GRB (Group of Experts on Vehicle Noise, World Forum for Harmonization of Vehicle Regulations, United Nations Working Party 29), has approved an international guideline(4) that is basically similar to that of the Japanese MLIT. The QRTV is also developing a global technical regulation (GTR) regarding he requirements for sound-emitting devices. In the United States, the Pedestrian Safety Enhancement Act of 2010 has been approved, which mandates the NHTSA to establish performance requirements for alert sounds that

[1] n_yasui@matsue-ct.jp
[2] miura@mail.ryukoku.ac.jp

would enable blind and other pedestrians to be reasonably aware of nearby EVs/HEVs. The automobile industry has also been working on the development of sound-emitting devices and the design of the actual sound itself. Indeed, some automobile manufacturers have launched warning systems for their EVs/HEVs(5). The problem of the quietness and the measures using additional warning sounds are one of the most important issue in environmental acoustics recently(6).

Various sounds were synthesized in previous studies(7-10). However, quiet vehicles are still problematic for pedestrians. Those studies had two problems. The first was that the sounds did not resemble those sounds of gasoline powered vehicles, and the second was that they were too noisy for people. Although the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) prepared guideline for warning sounds to prevent people from being inconvenienced(3), any sound that has met the guidelines has not yet been proposed.

It is assumed that pedestrians were aware of approaching gasoline powered vehicles by hearing the sounds of exhausts. Thus, pedestrians would be aware of approaching HVs or EVs by hearing them approach with amplitude fluctuations in the exhaust sounds of gasoline powered vehicles. Past studies(11-12) have shown that modulated sounds elicit the sensation of hearing fluctuations, or fluctuation strength. So, motor sounds with large fluctuation strength are expected to make it easier for pedestrians to become aware of approaching vehicles than sounds with small fluctuation strength. Our previous studies(13-17) found that the amplitude fluctuation is effective to enable people to notice the approaching vehicles. Another previous study found that the exhaust sound of gasoline engine has the periodic amplitude fluctuation and non-periodic fluctuation(18-19). Also, it showed that these fluctuations affected fluctuation strength. Here, we investigate relationship between detectability and characteristics of amplitude fluctuation on warning sounds for quiet vehicle.

2. OUTLINE OF INVESTIGATION

We investigated relationship between detectability and characteristics of amplitude fluctuation on warning sounds for quiet vehicle(13-17). Past studies(11-12) have shown modulation frequency for amplitude-modulated sound as characteristics of amplitude fluctuation. Our previous studies(18-19) have shown deviation for time and amplitude for sounds as those characteristics. Those studies(18-19) investigated fluctuation strength in a tremolo produced by irregularly plucking the strings of a mandolin and exhaust sounds of various motorbikes. We proposed a challenging hypothesis that these sounds were modeled as amplitude modulation (AM) sound whose amplitude envelope was modulated, since deviation for time and amplitude occurred in that amplitude envelope. We defined "mechanical performance" as completely constant performance in terms of time and amplitude. The tremolo and exhaust sounds were therefore interpreted as sound that included deviations from mechanical performance. We presented the average fluctuation frequency and deviations for time and amplitude that comprised the fluctuating sounds as characteristics that affected fluctuation strength. The average fluctuation frequency represents characteristics of periodic fluctuation, and these deviations represent characteristics of non-periodic fluctuation. The deviation for time means the deviation from the mechanical onset time, defined as a completely constant inter-onset interval, i.e., the average fluctuation frequency. The deviation for amplitude is the deviation from the mechanical amplitude that is defined as the completely constant peak amplitude, where the level of mechanical amplitude is that of the highest peak amplitude in the fluctuating sound. Moreover, our previous studies(18-19) have shown the shape of envelope for sounds as those characteristics.

As a result, we found that that fluctuating motor sounds with low fluctuation frequency, for example 8 Hz, could be detected more accurately than fluctuating motor sounds with high fluctuation frequency, for example 20 Hz. Also, it's found that fluctuating motor sounds with both periodic and non-periodic fluctuations could be detected more accurately than fluctuating motor sounds with only periodic fluctuation. Moreover, it was investigated relationship between impression and amplitude envelope. As a result of factor analysis, the factors of "informing" and "familiarity" are obtained. It was revealed that characteristic of periodic amplitude fluctuation influences the factors of "familiarity". Also, it's found that shapes of envelope contribute to both factors of "informing" and "familiarity". However, effect of amplitude envelope on detectability wasn't examined. In this study, we investigated the effect.

3. SYNTHESIS OF PROPOSED WARNING SOUND

3.1 Outline of Synthesis

In investigations of the effect, the motor sounds with characteristics of fluctuations of gasoline engines were used. Those sounds were synthesized based on a procedure proposed in our previous study(16).

This study assumed that non-periodic fluctuation extracted from the exhaust sound of a gasoline powered vehicle made it easy for pedestrians to notice approaching quiet vehicles. However, fluctuating motor sounds with various non-periodic fluctuations cannot be synthesized using only extracted non-periodic fluctuation. Thus, we used a method of feature exaggeration for a scale performance on a piano, in which a performance can be suppressed or exaggerated on the basis of extracted features of the current performance that maintains its "trend (or progression tendency in time)".

The procedure for synthesizing fluctuating motor sounds is outlined in Fig.1. The synthesized sound has characteristics of fluctuations in gasoline powered vehicle. Deviations for time and amplitude were extracted from the exhaust sound of a gasoline powered vehicle, and these deviations were suppressed or exaggerated. Then, envelopes, i.e., modulation wave in AM, were set for these deviations. A sine curve was used as a modulation wave. Finally, amplitude-modulated motor sounds were synthesized using these sine curves. We call the motor sound that has been synthesized "fluctuating motor sound".

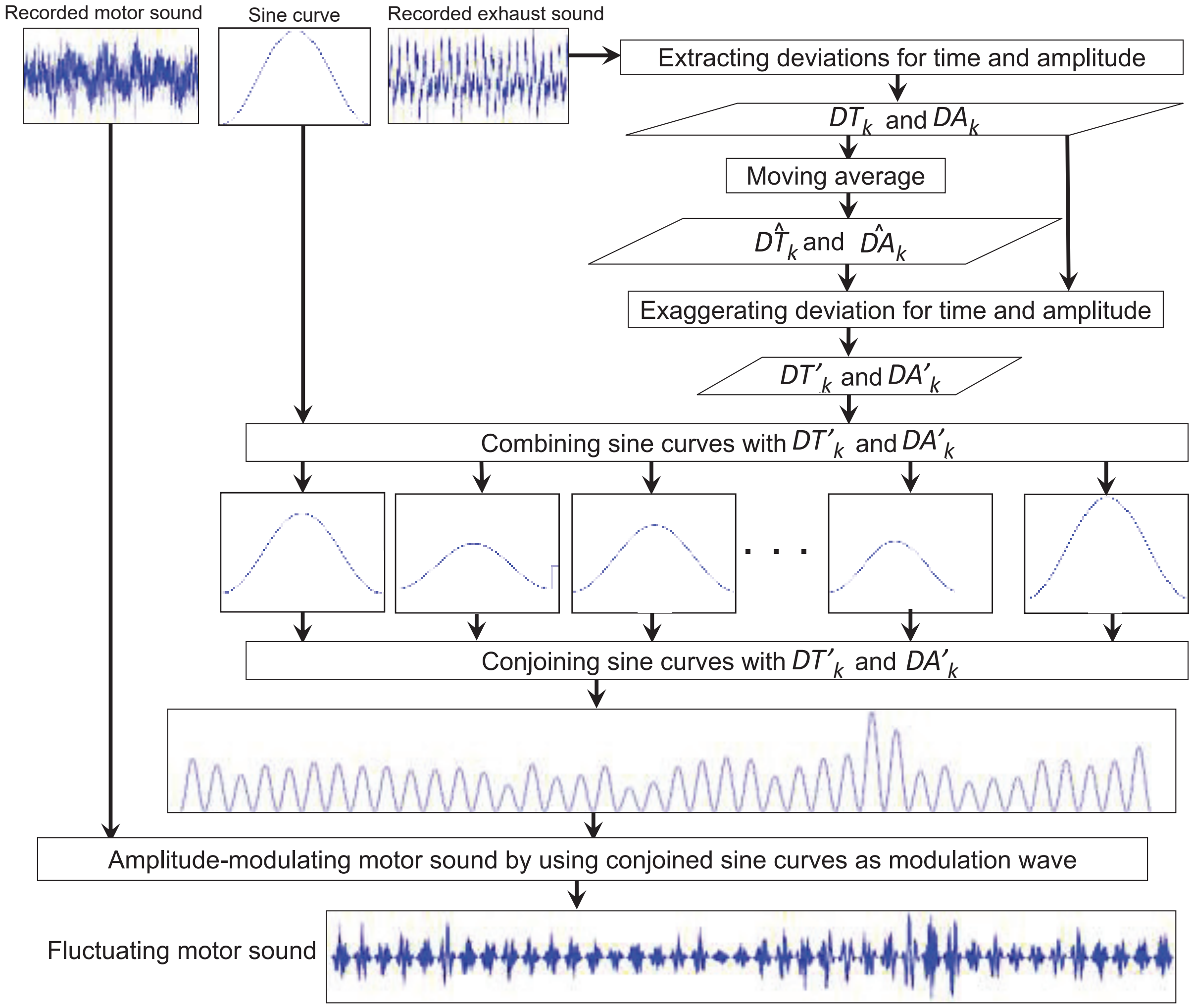


Figure 1 – Procedure for synthesizing fluctuating motor sound(16).

3.2 Extracting Deviation for Time and Amplitude

The sound from the motor of an EV and the sound from the exhaust of an idling gasoline powered vehicle were recorded with a microphone, and the onset times were estimated from the exhaust sound.

The deviation for time was extracted on the basis of the mechanical onset time and the deviation for amplitude was extracted on the basis of mechanical amplitude. These sounds were recorded outside using a microphone. The EV used for the recording was a Nissan Leaf (Nissan Motor Co. Ltd.). The gasoline powered vehicle used was a Demio (Mazda Motor Corporation). A microphone for recording the motor sound (AT899, Audio-Technica Corporation), another microphone for recording the exhaust sound (SM58, Shure Incorporated), and a recorder (DR-680, TEAC Corporation) were used. Sounds were recorded in 16 bits for each sample at a rate of 48 kHz.

The time when the maximum amplitude level occurred at every interval of an explosion in the engine was estimated as the onset time. The interval was obtained from result of estimating F0 for the envelope of exhaust sound. Then, the differences between the mechanical and estimated onset times were calculated. These differences were determined as the deviations for time, defined as DT_k (k = 1-N), where k represents the identification number of the onset time and N represents the total number of explosions. Each value of DT_k was calculated using the onset time with k = 1 as the standard. Also, the differences between the mechanical amplitude and amplitude at estimated onset times were extracted from an acoustic signal. These differences were determined as the deviations for amplitude, defined as DA_k.

3.3 Suppressing or Exaggerating Deviations for Time and Amplitude

Feature exaggeration that maintained the trend in actual exhaust sound was produced by controlling the feature parameters. The exaggeration was conducted for extracted deviations, as well as that in our previous procedure(18-19).

First, we calculated the deviation trend curves for time and amplitude, where the moving average for these deviations was calculated for three samples. Then, we suppressed or exaggerated these deviations for four features using deviation trend curves. The first was the sum of the difference between the extracted deviation and the deviation trend curve, the second was the range in the deviation trend curve, the third was the sum of the difference between successive explosions on the deviation trend curve, and the fourth was the sum of the differences between the completely constant inter-onset interval of an explosion and the deviation trend curve. The details of suppression or exaggeration by the feature exaggeration method are as follows:

$$x'_{i,1} = \hat{x}_i + C_{i,1}(x_i - \hat{x}_i) \tag{1}$$

$$M = \frac{\max(\hat{x}_i) + \min(\hat{x}_i)}{2} \tag{2}$$

$$x'_{i,2} = M + C_{i,2}(\hat{x}_i - M) \tag{3}$$

$$S_{\mathrm{U}}(z) = \frac{\max(\hat{x}_i) - \min(\hat{x}_i)}{N-1} z + \min(\hat{x}_i) \tag{4}$$

$$S_{\mathrm{L}}(z) = \frac{\min(\hat{x}_i) - \max(\hat{x}_i)}{N-1} z + \max(\hat{x}_i) \tag{5}$$

$$x'_{i,3} = \begin{cases} S_{\mathrm{L}} + C_{i,3}(\hat{x}_i - S_{\mathrm{L}}) & (\sum|S_{\mathrm{L}} - \hat{x}_i| < \sum|S_{\mathrm{U}} - \hat{x}_i|) \\ S_{\mathrm{U}} + C_{i,3}(\hat{x}_i - S_{\mathrm{U}}) & (\sum|S_{\mathrm{L}} - \hat{x}_i| > \sum|S_{\mathrm{U}} - \hat{x}_i|) \end{cases} \tag{6}$$

$$x'_{i,4} = C_{i,4}\hat{x}_i \tag{7}$$

Here, x_i represents deviations for time (i = 1) or deviations for amplitude (i = 2), $\hat{x}_i$ represents the deviation trend curve for each deviation, $C_{i,r}$ is the ratio for suppressing or exaggerating each feature, and $x'_{i,r}$ is the suppressed or exaggerated deviations for time or amplitude for the rth feature. $x'_{i,1}$ is obtained by manipulating the difference between extracted deviations and the deviation trend curve of each explosion. $x'_{i,2}$ is obtained by manipulating the range of the deviation trend curve. M represents the half-range of the deviation trend curve. $x'_{i,3}$ is obtained by manipulating the difference between the deviation trend curve and a standard straight line that connects the maximum and minimum points on the deviation trend curve. The simple increasing straight line is defined as S_U, and the decreasing line is defined as S_L. The straight line for which the sum of the differences between the deviation trend curve and straight line is the minimum is assumed to be the standard. $x'_{i,4}$ is obtained by manipulating the average difference between the deviation trend curve and the completely constant inter-onset interval of an explosion.

3.4 Setting Deviations for Envelope on Amplitude-Modulated Motor Sound

A sine curve was used as envelope on one period in setting the deviations for the envelope. Modulation waves, or sin curves with one period were set to the suppressed or exaggerated deviations for time and amplitude to synthesize envelope, and these curves were alternately conjoined. Next, amplitude-modulated motor sounds were synthesized using a conjoined sine curve as a modulation wave.

4. EXPERIMENT

4.1 Outline of Experiment

We conducted an evaluation experiment with six listeners in a soundproof room to examine effect of amplitude envelope on detectability. Our previous study showed that fluctuating motor sounds with low fluctuation frequency, for example 8 Hz, could be detected more accurately than fluctuating motor sounds with high fluctuation frequency, for example 20 Hz. Also, it's found that fluctuating motor sounds with both periodic and non-periodic fluctuations could be detected more accurately than fluctuating motor sounds with only periodic fluctuation. Moreover, it was investigated relationship between impression and amplitude envelope, our results found that shapes of envelope contribute to both factors of "informing" and "familiarity". But, effect of amplitude envelope on detectability wasn't examined. In this experiment, we investigated the effect.

4.2 Method

The adjusted acoustic sound levels for fluctuating motor sounds with periodic and non-periodic fluctuations were investigated. The stimuli were a total of 27 fluctuating motor sounds (3 fluctuation frequencies × 3 deviation patterns × 3 envelope patterns). These sounds were synthesized using the procedure described Section 3. The fluctuation frequencies were 8, 14 and 20 Hz, and the deviation patterns were 4 combined pattern (no deviations, only DA, and DT&DA). In case of "no deviation", the exaggeration ratios for both DT and DA were 0 %. In case of "only DA", the exaggeration ratio for DT was 0 % and the one for DA was 200 %. In case of "both DT and DA", the exaggeration ratio for both DT and DA were 200 %. The envelopes of fluctuating motor sound were sine wave, sawtooth wave, and rectangle wave. The environmental sound used in this experiment was pink noise. The levels of acoustic power of the stimuli were equalized. Stereo sounds perceived as if a car is approaching listener and departing from listener were presented in this experiment. Fluctuating motor sound with taper was synthesized in the left channel, the sound with taper was synthesized 0.25 sec late from left channel in the right channel. The length of taper was 1 sec.

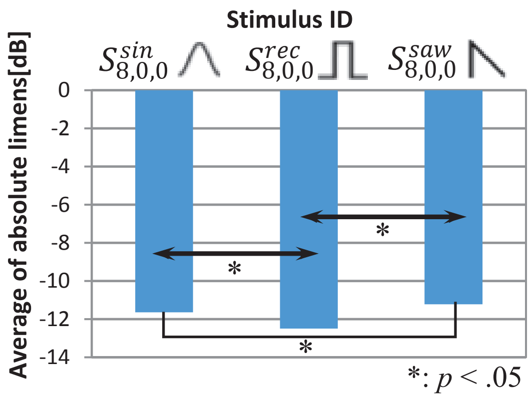
We used the method of limits in this experiment. The acoustic levels of stimuli were gradually increased in 1 dB steps until they were just detectible. The procedure was also run in reverse with a decrease in the intensity of stimuli until they could no longer be detected. The listeners gave a binary (YES/NO) response to indicate whether they could detect stimuli in situations in which an environmental sound was also presented. Three descents and three ascents were used in each stimulus. The stimuli were presented to the listeners through a pair of earspeakers. Electrostatic earspeakers (SR-307, STAX Ltd.) and an amplifier (SRM-323S, STAX Ltd.) were used for the evaluation. Listeners were allowed to adjust the acoustic sound level before the experiment to one that best enabled them to listen to the fluctuating motor sounds. The average level was about L_A = 54.8 dB.

4.3 Result

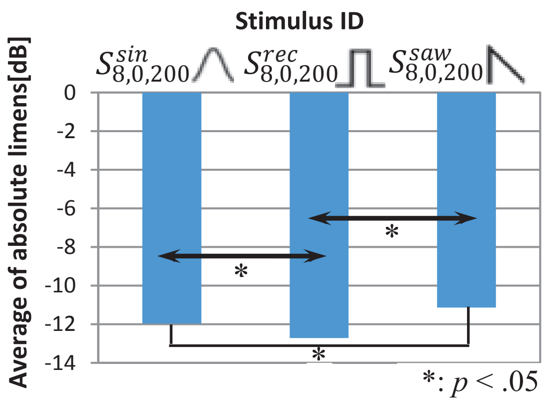
Each results from the evaluation experiment are given in Fig. 2-4. The vertical axis represents the average absolute limens (AL) for the subjective scores of all listeners. The scores for each listener were obtained by calculating the arithmetic mean for each subjective score for each stimulus. The $S^{\sin}_{f,dt,da}$ (f = 8, 14, 20, dt = 0, 100; da = 0, 200) mean fluctuating motor sounds with sine wave, $S^{\mathrm{rec}}_{f,dt,da}$

mean fluctuating motor sounds with rectangle wave, $S^{\mathrm{saw}}_{f,dt,da}$ mean fluctuating motor sounds with sawtooth wave.

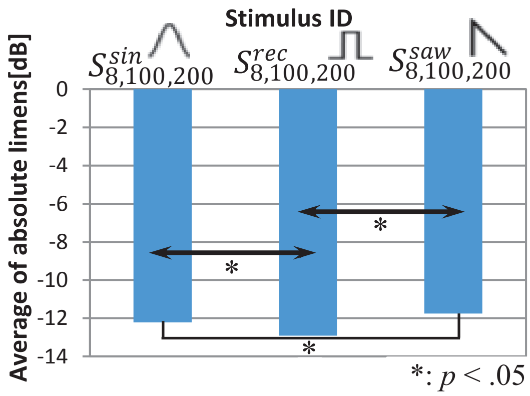
As can be seen from Fig. 2, we found that the average AL of $S^{\mathrm{rec}}_{8,dt,da}$ was smaller than that of $S^{\mathrm{sin}}_{8,dt,da}$ and $S^{\mathrm{saw}}_{8,dt,da}$. Thus, this result showed that fluctuating motor sounds with rectangle wave had smaller AL than fluctuating motor sounds with other waves in case of fluctuation frequency of 8 Hz. It was observed that there are little differences among that of $S^{\mathrm{rec}}_{8,dt,da}$, $S^{\mathrm{sin}}_{8,dt,da}$ and $S^{\mathrm{saw}}_{8,dt,da}$, as shown in Fig.3 and 4. Thus, this result showed that the lowest acoustic sound level for fluctuating motor sounds with rectangle wave was lower than the level for fluctuating motor sounds with other waves in case of only 8 Hz.



(a) no deviation



(b) only DA



(c) DT&DA

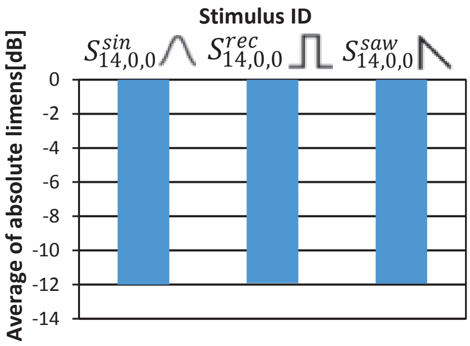
Figure 2 – Results of experiment for deviations for time and amplitude in fluctuation frequency of 8 Hz.

5. DISCUSSION

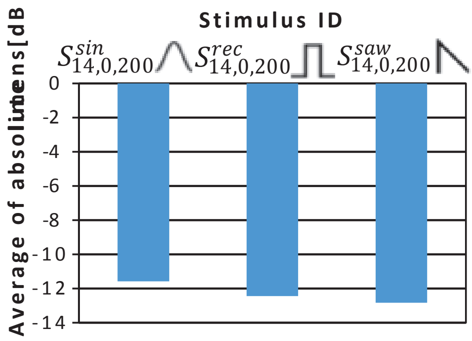
We found from the results that the effects of amplitude envelope in fluctuation frequency of 8 Hz is higher than the one in the frequency of 14 and 20 Hz. The analysis of variance was conducted for each AL. For each envelope, significant differences among each stimulus are confirmed($p < .05$). As a result of analysis of variance, it was confirmed that the main effect is significant in each envelope($p < .05$). Then, our results showed that amplitude envelope is effective to enable people to notice the approaching vehicles in fluctuation frequency of only 8 Hz.

The reason why there is effect of amplitude envelope in fluctuation frequency of only 8 Hz is described as follows. Past studies(11-12) found that the sensation of hearing fluctuations is elicited for modulated sounds with a modulation frequency of up to around 20 Hz. It was showed that the sensation from an AM pure tone with a modulation frequency within 4–8 Hz is greater than that outside this range, and the strongest sensation for fluctuation is obtained within 4–8 Hz. So, it is assumed that amplitude envelope influences detectability in fluctuation frequency of only 8 Hz because the sensation in 8 Hz is greater than those in 14 and 20 Hz.

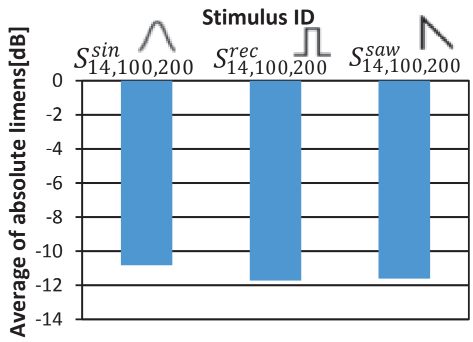
Therefore, we found that motor sounds fluctuated by rectangle wave make it easier for pedestrians to become aware of approaching vehicles than sounds fluctuated by sine and sawtooth waves. We



(a) no deviation

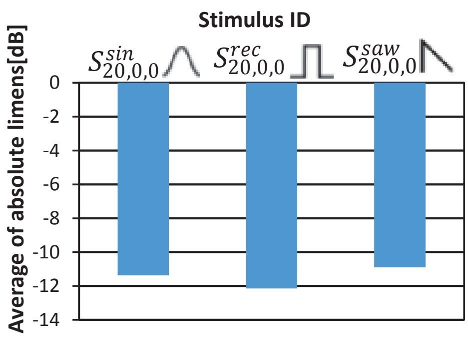


(b) only DA

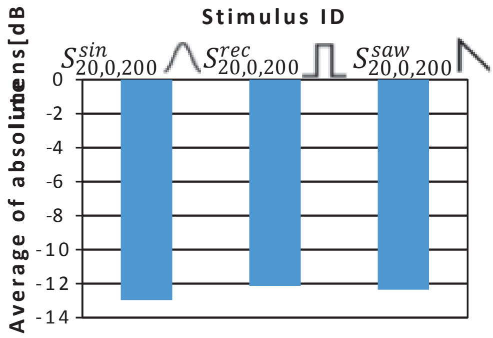


(c) DT&DA

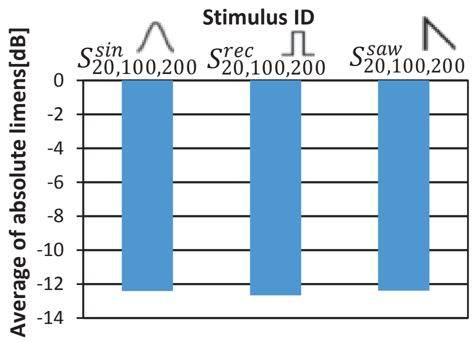
Figure 3 – Results of experiment for deviations for time and amplitude in fluctuation frequency of 14 Hz.



(a) no deviation



(b) only DA



(c) DT&DA

Figure 4 – Results of experiment for deviations for time and amplitude in fluctuation frequency of 20 Hz.

presented current warning sound that used rectangle wave and non-periodic fluctuations in exhaust sounds to enhance the detectability of approaching quiet vehicle. However, our results did not sufficiently demonstrate the combined effects of characteristics of fluctuation and fluctuated sound type, not motor sound but other sounds. These effects will be discussed in the near future.

6. CONCLUSIONS

We investigated the effect of the envelope on detectability of warning sound for quiet vehicle. Our results revealed that the shape of envelope influences the ability with which people detect approaching quiet vehicles in case of slow fluctuation frequency.

We plan to examine what effect the progressive tendencies of these deviations have on detectability, to examine sounds amplitude-modulated by using not motor sound but other sounds, and to conduct evaluation experiment simulated real environment.

ACKNOWLEDGEMENTS

This study was partly supported by the Grants-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (15H02882, 15K12299, 16H03021).

REFERENCES

1. Incidence of Pedestrian and Bicyclist Crashes by Hybrid Electric Passenger Vehicles. National Highway Traffic Safety Administration, DOT-HS-811-204, 2009.
2. National Federation of the Blind. Key Stakeholders Agree on Measures to Protect Blind Pedestrians from Silent Cars —Urge Passage as Part of Motor Vehicle Safety Act. https://nfb.org/node/1056 (referred 2014-08-11).
3. Japanese Automobile Standards International Centre, "A study on approaching warning systems for hybrid vehicle in motor mode", Informal document No GRB-49-10, (2009)
4. Proposal for guidelines on measures ensuring the audibility of hybrid and electric vehicles. in Consolidated Resolution on the Construction of Vehicles (R.E.3), Annex 2, ECE/TRANS/WP.29, Geneva, Swizerland, 2011.
5. Tabata, H. Konet, and T. Kanuma, "Development of Nissan Approaching Vehicle Sound for Pedestrians", Proc. of Inter-noise 2011, DVD-ROM Wed-8-8, Sep. 2011; Osaka, Japan 2011.
6. K. Yamauchi, "A discussion on the problem of quietenss of hybrid and electric vehicles and additional warning sound for these vehicles", Proc. Forum Acusticum 2014, PJ06_6, Sep. 2014; Krakow, Poland 2014.
7. Genuit K. Particular Importance of Psychoacoustics for Sound Design of Quiet Vehicles. Proc. of Inter-noise 2011, CD-ROM, Wed-8-10, Sep. 2011; Osaka, Japan 2011.
8. Wolff K, Eisele G, Genender P, and Schürmann G. Acoustics of electric vehicles with range extender. Proc. of Inter-noise 2011, CD-ROM, Wed-8-11, Sep. 2011; Osaka, Japan 2011.
9. Van der Auweraer H, Janssens K, Sabbatini D, Sana E, and De Langhe K. Electric Vehicle Exterior Sound and Sound Source Design for Increased Safety. Proc. of Inter-noise 2011, CD-ROM, Wed-8-13, Sep. 2011; Osaka, Japan 2011.
10. Ming Une Jen and Ming-Hung Lu. Warning sound of electric vehicle for pedestrian safety. Proc. of Inter-noise 2011, CD-ROM, Wed-8-15, Sep. 2011; Osaka, Japan 2011.
11. Fastl H. Fluctuation strength and temporal masking patterns of amplitude modulated broadband noise. Hearing Research 1982; 8(1): 56-69.
12. Zwicker E and Fastl H. Psychoacoustics Facts and Models. Springer-Verlag Berlin Heidelberg; 2007. pp. 247-256, (1990)
13. Yasui N and Miura M. Approaching electric vehicles sound for pedestrians based on ease of detection by fluctuation of motor sound. Proc. of Inter-noise 2012, 738, Aug. 2012; New York, USA 2012.
14. Yasui N and Miura M. Effect of non-periodic fluctuation sound for detectability of approaching quiet vehicle. Inter-noise 2013, 667, Sep. 2013; Innsbruck, Austria 2013.
15. Yasui N and Miura M. Relationship between characteristics of amplitude fluctuation and detectability of warning sounds for electric vehicle. Proc. Forum Acusticum 2014, SS28_13, Sep. 2014; Krakow, Poland 2014.
16. Yasui N and Miura M. Relationship between detectability and fluctuation strength of warning sounds for quiet vehicle. Proc. of Inter-noise 2015, 728, Aug. 2015; San Francisco, USA 2015.
17. Yasui N. Subjective evaluation of amplitude fluctuated sounds that warn of approaching quiet vehicle. Proc. of Inter-noise 2015, 742, Aug. 2015; San Francisco, USA 2015.
18. Yasui N, Miura M and Kataoka A. Procedure for estimating fluctuation strength from tremolo by irregular plucking of mandolin. Acoustical Science and Technology 2012; 33(3):160-169.
19 Yasui N and Miura M. Estimating Fluctuation Strength for exhaust sound of motorbikes with 1st, 2nd and 3rd fluctuations. Proc. of Inter-noise 2011, CD-ROM, Mon-8-10, Sep. 2011; Osaka, Japan 2011.