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# COMMAND FILTERED-X LMS ALGORITHM AND ITS APPLICATION TO CAR INTERIOR NOISE FOR SOUND QUALITY CONTROL

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Abstract. *In recent years, an increasing number of cars are being manufactured incorporating the active noise control (ANC) technology. This technology is being used not only for noise reduction but also for imparting the impression of an even engine running sound. Thus, engine sound control has shifted from noise reduction to sound design. To determine the desired engine sound, we investigate the relationship between each order component of the engine sound and the related auditory impression. The spectrum of each order component is not a constant level; it includes peaks and dips. In an auditory experiment, five stimuli obtained by signal processing, such as spectrum interpolation and elimination of a specific order component, were presented to 20 healthy volunteers and the scale values of preference were obtained using the semantic differential method. It was determined that the elimination of the second-order component improved the sporty feeling. Therefore, the engine sound impression can be changed by adjusting the spectrum power level, using ANC. To change the engine noise to the desired sound, we apply the command filtered-x LMS algorithm to an actual car. The harmonic structure of the car interior noise can be observed more clearly when controlled by this algorithm.*
**Keywords:** Active noise control, Command filtered-x LMS algorithm, Car engine noise, Sound quality control

1. **Introduction.** With the continuing advances in digital signal processing technology, the active noise control (ANC) technology [1] has received attention as a potential noise reduction measure. The ANC technology reduces noise by superimposing a sound on a target, where the sound has the same amplitude but an opposite phase. The ANC technology has a number of advantages. First, it is effective in the removal of low-frequency noise, which is difficult to reduce using conventional passive reduction methods, such as the application of sound-insulating, sound-absorbing, or damping materials [2]. Further, the ANC technology can be implemented in smaller spaces than the conventional passive reduction methods. Therefore, this technology is currently used in car interior noise reduction [3,4]. However, driving a car can be considered a leisure activity [5] and certain reductions in the level of noise can reduce the driving pleasure, the fun of driving, or the "sporty" feeling for the driver. Thus, control of the engine sound has shifted towards sound design, rather than actual noise reduction [6]. This type of sound design has been actively studied by automobile manufacturers [7,8].

Some algorithms used for noise reduction have been already applied [9,10]. As an example, the filtered-x LMS algorithm is widely used for ANC, and it controls the sound field to zero. However, no algorithm has been proposed for sound quality control. The proposed command LMS algorithm is used for sound quality control and to control the sound field to approach the command sound. Therefore, we adopt this algorithm to evaluate the sound quality of a car interior.

Furthermore, to determine that the desired sound is the drivers' preferred sound, we need to know the relationship between the harmonic structure of the engine sound and auditory impression. Therefore, the relationship between them was evaluated in order to control the engine sound to the preferred sound. Although the sound quality control has already been studied [11], there is no research comparing the sound quality control with individual preferences.

In this paper, firstly, we introduce the algorithm for sound quality control. Secondly, we investigate the relationship between the car engine sound and related auditory impression, to determine the desired sound preferred by drivers. Finally, we apply the command filtered-x LMS algorithm [12] to an actual car interior noise to changing the existing sound into the desired car engine sound.

2. **Algorithm.** We require a method to change the car engine noise to the desired sound. In this study, we employ the command filtered-x LMS algorithm, which is an extension of the filtered-x LMS algorithm. This section describes both algorithms.

2.1. **Filtered-x LMS algorithm.** The filtered-x LMS algorithm is represented as a block diagram in Figure 1. This figure shows the reference signal $x(n)$, control signal $u(n)$, disturbance signal $d(n)$, and error signal $e(n)$. $W(z)$ is the adaptive filter, $G(z)$ denotes the plant response, and $\hat{G}(z)$ represents the plant estimate.

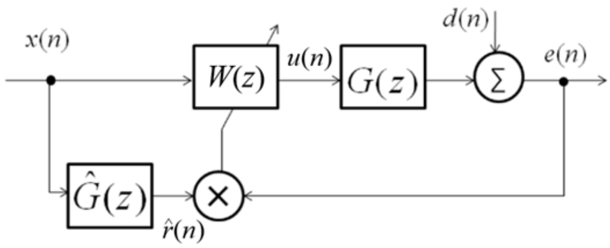


FIGURE 1. Block diagram of filtered-x LMS algorithm

The form of the LMS update equation is therefore

$$W(n+1) = W(n) - \alpha\hat{r}(n)e(n) \tag{1}$$

where $\alpha$ is the convergence coefficient.

The filtered-x LMS algorithm uses the filtered reference signal, $\hat{r}(n)$, to update the weights of the adaptive digital filter, $W(z)$. The filtered-x LMS algorithm minimizes the error signal, $e(n)$; therefore, this algorithm is frequently used for noise reduction.

2.2. **Command filtered-x LMS algorithm.** The command filtered-x LMS algorithm is represented as a block diagram in Figure 2. This figure shows the reference signal $x(n)$, control signal $u(n)$, disturbance signal $d(n)$, error signal $e(n)$, pseudo error $e'(n)$, and command signal $c(n)$. $W(z)$ is the adaptive filter, $G(z)$ denotes the plant response, and $\hat{G}(z)$ represents the plant estimate.

The form of the LMS update equation is therefore

$$W(n+1) = W(n) - \alpha\hat{r}(n)e'(n) \tag{2}$$

where $\alpha$ is the convergence coefficient. The vector of the pseudo error signals can be written as

$$e'(n) = e(n) - c(n) \tag{3}$$

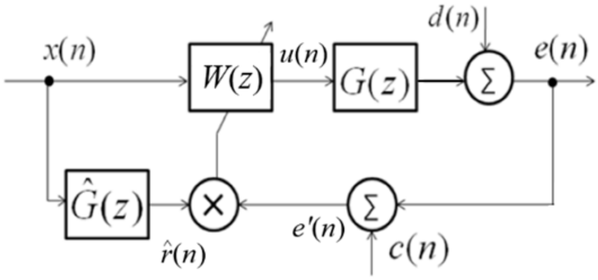


FIGURE 2. Block diagram of the command filtered-x LMS algorithm

This algorithm is essentially the same as the filtered-x LMS algorithm, which uses a filtered reference signal, $\hat{r}(z)$, to update the weights of the adaptive digital filter, $W(z)$, except that the command filtered-x LMS algorithm minimizes the pseudo error signal, $e'(n)$, instead of the true error signal, $e(n)$. This pseudo error misleads the filtered-x LMS algorithm into converging to a desired output command signal, $c(n)$. Therefore, this algorithm is proposed for sound quality control.

The command signal is created from the reference signal, $x(n)$, which ensures that its frequency components are the same as those of the disturbance signal.

Thus, the command LMS algorithm was proposed as the algorithm to approximate the desired signal to the command signal. In this study, the command LMS algorithm was adopted to the actual sound for sound quality control.

3. **Study of Impression Variation of Car Sound Quality.** In this section, we perform auditory experiments using a semantic differential method to determine the relationship between the car engine sound and auditory impression.

The car engine sound can be divided into full-order and half-order components. Engine sounds originated from the full-order components are known to “feel” comfortable. Conversely, half-order components are subject to noise control because they are unpleasant sounds. However, the relationship between the harmonic structure and the auditory impression of the engine sound remains unclear. To determine the sound desired for the engine sound, we investigate this relationship.

3.1. **Stimulus.** The command filtered-x LMS algorithm can be used to adjust the spectrum power level of the engine sound. Thus, we must determine the relationship between the harmonic structure and auditory impression of the engine sound. Table 1 presents the stimuli, which are obtained by signal processing using spectrum interpolation and elimination of specific order component. These stimuli are used in the auditory experiments.

TABLE 1. Stimuli

| | |
|---|---|
| **Stimulus 1** | Intake sound |
| **Stimulus 2** | Spectrum interpolation of Stimulus 1 |
| **Stimulus 3** | Elimination of half-harmonic from Stimulus 2 |
| **Stimulus 4** | Elimination of $2^{\text{nd}}$ harmonic from Stimulus 2 |
| **Stimulus 5** | Elimination of half and $2^{\text{nd}}$ harmonics from Stimulus 2 |

The vehicle used in this study was a left-hand drive sedan vehicle with a four-cylinder four-cycle engine. The interior and intake noises were recorded using a microphone at a sampling frequency of 6000 Hz. The driving conditions were acceleration in the third gear, with a wide-open throttle from 1000 to 6000 rpm for approximately 20 s.

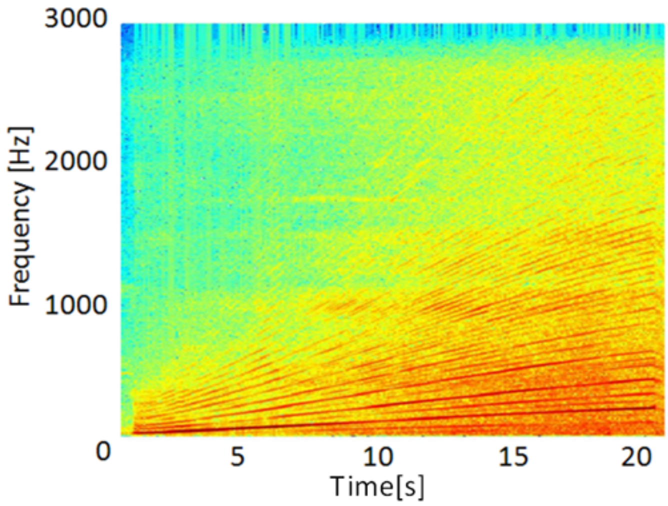


FIGURE 3. Intake sound (Stimulus 1)

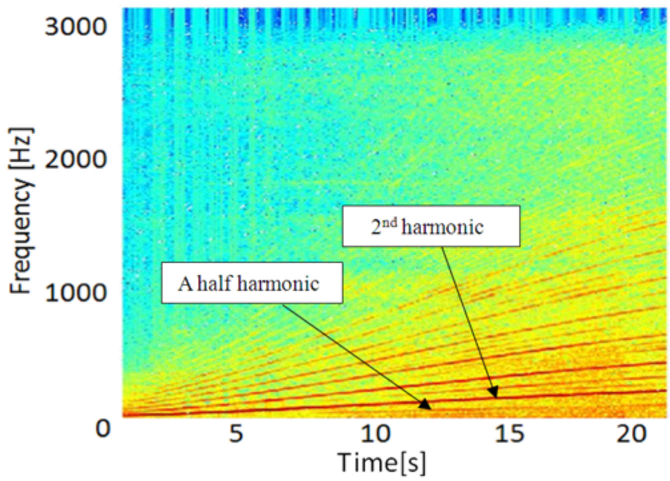


FIGURE 4. Stimulus 2

Figure 3 shows a spectrogram of the intake noise. Stimulus 1 of the base stimuli is the intake noise.

Figure 4 shows a spectrogram of Stimulus 2. Because Stimulus 1 indicated a reduction in the spectrum power, Stimulus 2 is the spectrum power interpolation of Stimulus 1.

Figure 5 shows a spectrogram of Stimulus 3. Because half-order components are subject to noise control as unpleasant sounds, Stimulus 3 is produced by the elimination of a half-harmonic from Stimulus 2.

Figure 6 shows a spectrogram of Stimulus 4. Stimulus 4 is produced by the elimination of a second harmonic from Stimulus 2.

Figure 7 shows a spectrogram of Stimulus 5. Stimulus 5 is produced by elimination of the second and a half-harmonic from Stimulus 2.

3.2. **Auditory experiment.** In this section, we perform auditory experiments using a semantic differential method to determine the relationship between the car engine sound and the auditory impression.

The stimuli were presented to 20 healthy volunteers, composed of 16 males and 4 females, with ages ranging from 20 to 23 years old; they all held a driver's license. Table 2 presents the adjective pairs. Each stimulus was presented twice in random sequence.

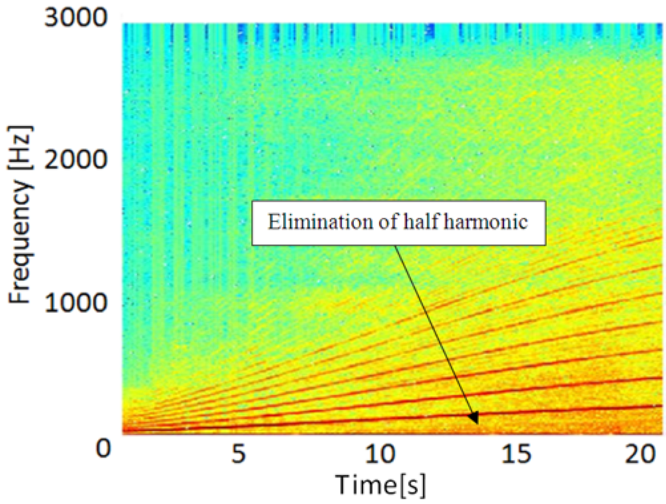


FIGURE 5. Stimulus 3

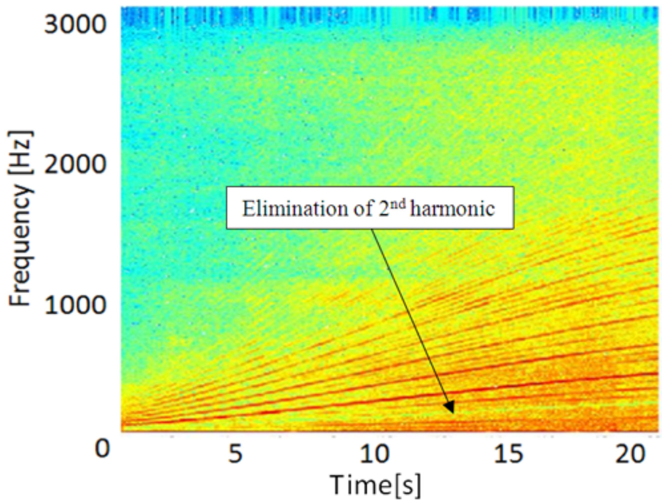


FIGURE 6. Stimulus 4

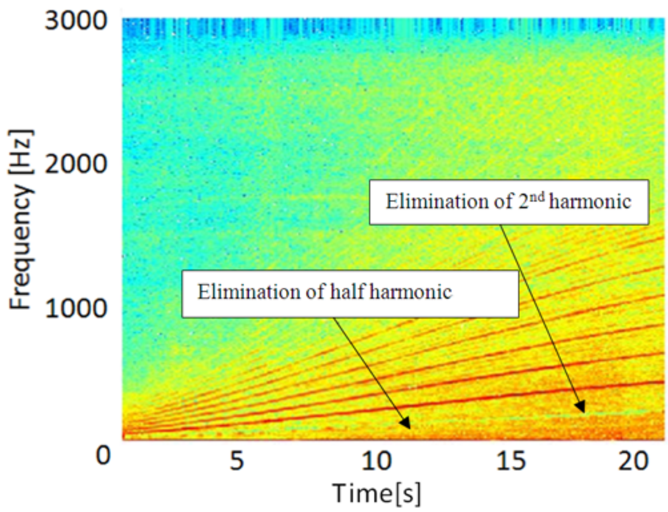


FIGURE 7. Stimulus 5

TABLE 2. Adjective pairs

| | | |
|---|---|---|
| **1** | **Fast** | **Late** |
| **2** | Powerful | Weak |
| **3** | Brilliant | Dull |
| **4** | Sporty | Non-sporty |
| **5** | Clear | Dirty |
| **6** | Pleasurable | Unpleasant |
| **7** | Quiet | Noisy |
| **8** | Light | Heavy |
| **9** | Luxury | Cheap |
| **10** | Sumptuous | Simple |
| **11** | Sharp | Blunt |
| **12** | Bright | Dark |
| **13** | High | Low |

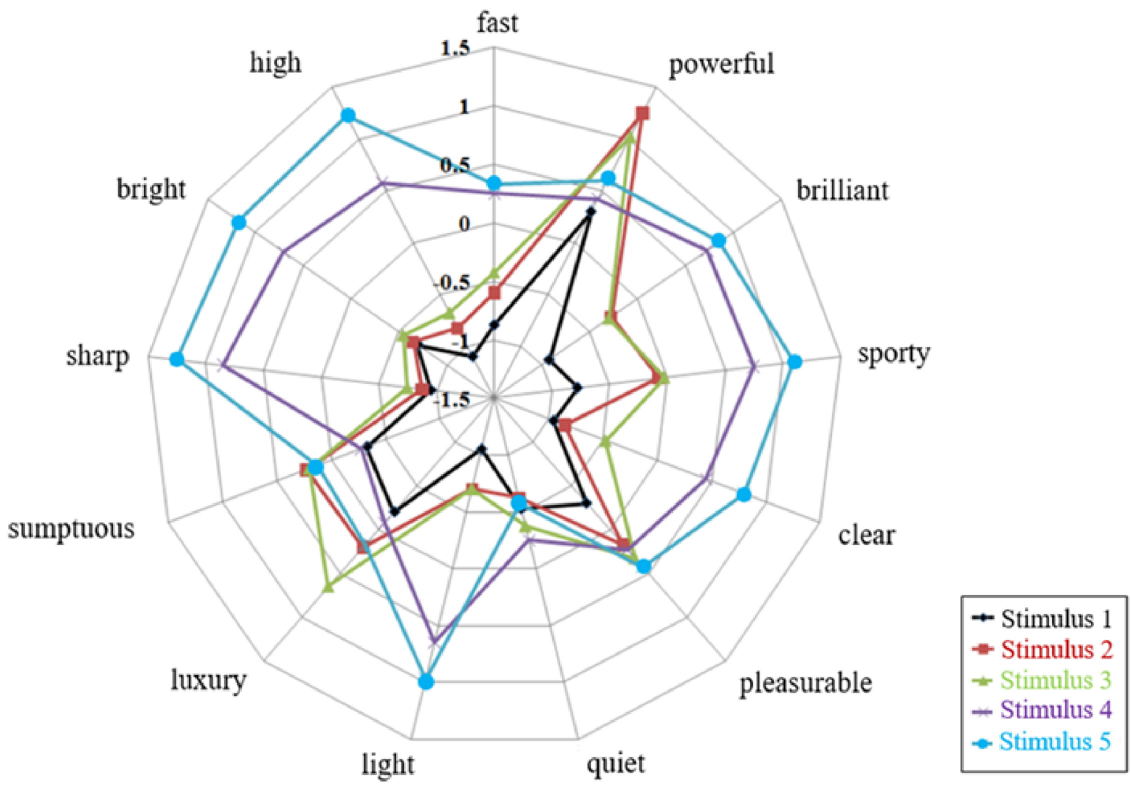


FIGURE 8. Results of auditory evaluation

The participants were requested to determine their preferred sound to create a scaled preference value rated on a scale of $-3$ to 3 with thirteen adjective pairs.

Figure 8 shows the results of the auditory evaluation. For the majority of the adjective pairs, Stimulus 1 indicated the lowest score. Stimulus 4 and Stimulus 5 had higher evaluation scores for “high” and “bright”. Further, these stimuli had greater evaluation scores for “sporty” and “sharp”, which indicate sporty feelings.

Stimulus 2 and Stimulus 3 indicated low scores for “high” and “bright”. These stimuli also had high scores for “powerful”. Therefore, these stimuli were evaluated higher for “luxury”.

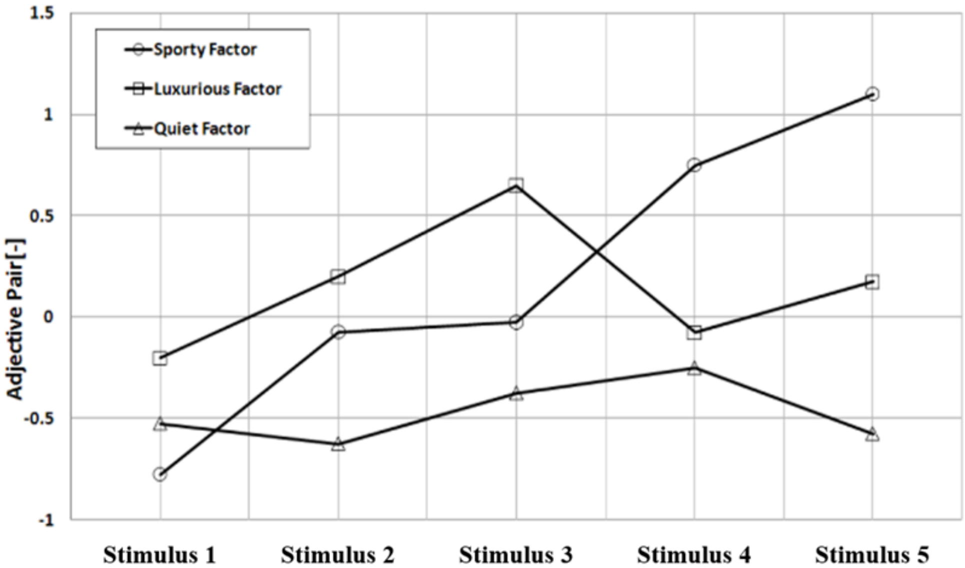


FIGURE 9. Results of data analysis

Figure 9 shows the results of the data analysis. In these results, the sport factor increased the scores of all stimuli. Spectrum interpolation and elimination of a half-harmonic and the second harmonic also increased the sport factor score. Spectrum interpolation and elimination of a half-harmonic increased the luxury factor score. However, elimination of the second harmonic reduced the luxury factor score. The reason for this is that the elimination of the second harmonic produces a lighter sound. A half-order in the car engine sound reduced both the sporty feeling and luxury factor. Further, a reduction in the spectrum power also decreased the sporty feeling and the luxury factor score. The impression of the car engine sound was improved by adjusting the spectrum power level. The elimination of the second-order component of the car engine sound also improved the sporty feeling. Therefore, the sporty feeling of the sound can be improved using ANC. The command filtered-x LMS algorithm can be used to adjust the spectrum power level.

4. **Study of Use on Actual Sound.** As automobile manufacturers have attempted to portray the intake noise in a car as a sound with a sense of sportiness, the control signal $c(n)$ is the intake sound. Hence, the control approach is based on the control of the interior noise in the intake sound, with the aim of increasing the sporty feeling for the driver. The reference signal $x(n)$ is the intake sound. The disturbance signal $d(n)$ is the interior sound. The driving conditions were acceleration in the third gear, with a wide-open throttle from 1000 to 6000 rpm for approximately 20 s.

Figure 10 shows the controlled interior sound characteristics. Figure 11 shows the interior sound characteristics. When compared with the interior sound, the harmonic structure of the controlled interior sound can be observed more clearly. However, the control has not been performed to a sufficient level. One reason for this is that the noise disturbances increase as the engine speed increases. Another reason is the setting of the convergence coefficient. As the engine speed increases, the amplitude increases. Furthermore, as the amplitude increases, the convergence coefficient increases. Therefore, the large convergence coefficient makes the control unstable.

Figure 12 shows the differences between the control signal $c(n)$ and the controlled interior noise $e(n)$. As the engine speed increases, the errors also increase. At speeds

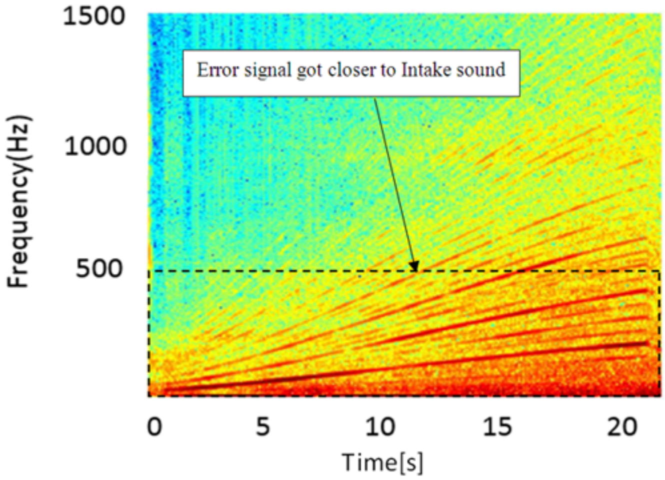


Figure 10. Controlled interior sound

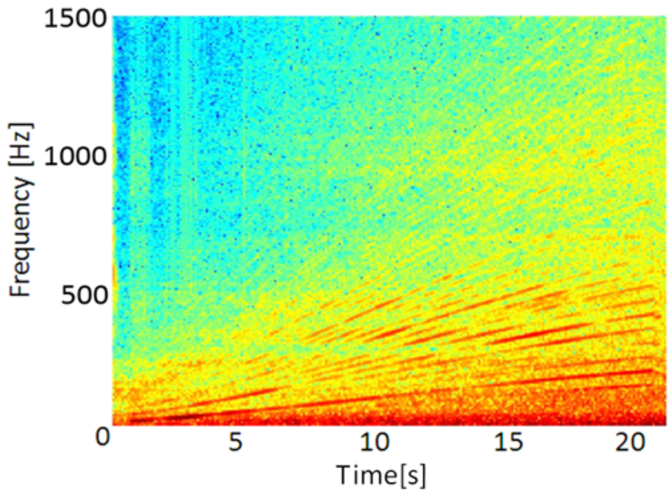


Figure 11. Interior sound

of more than 5000 rpm, the errors increase remarkably. Hence, the necessity to provide countermeasures to address this disturbance is indicated.

From Figure 10 and Figure 11, when compared with the interior sound, the harmonic structure of the controlled interior sound can be observed more clearly. Therefore, the command LMS algorithm can control the harmonic structure. Furthermore, the command LMS algorithm can control the sound quality.

5. **Conclusions.** We investigated the relationship between a car engine sound and the auditory impression to determine the desired sound as the engine sound. Furthermore, we applied the command filtered-x LMS algorithm to an actual car interior noise for sound quality control.

In the results of the auditory evaluation, the spectrum interpolation indicated higher evaluation scores for “high” and “bright”. The elimination of a half-harmonic and the second harmonic also had higher evaluation scores for “high” and “bright”. Further, these stimuli had higher evaluation scores for “sporty” and “sharp”, which indicate sporty feelings. The elimination of the second harmonic resulted in low scores for “high” and “bright”. These stimuli also had high scores for “powerful”. Therefore, these stimuli are evaluated higher for “luxury”.

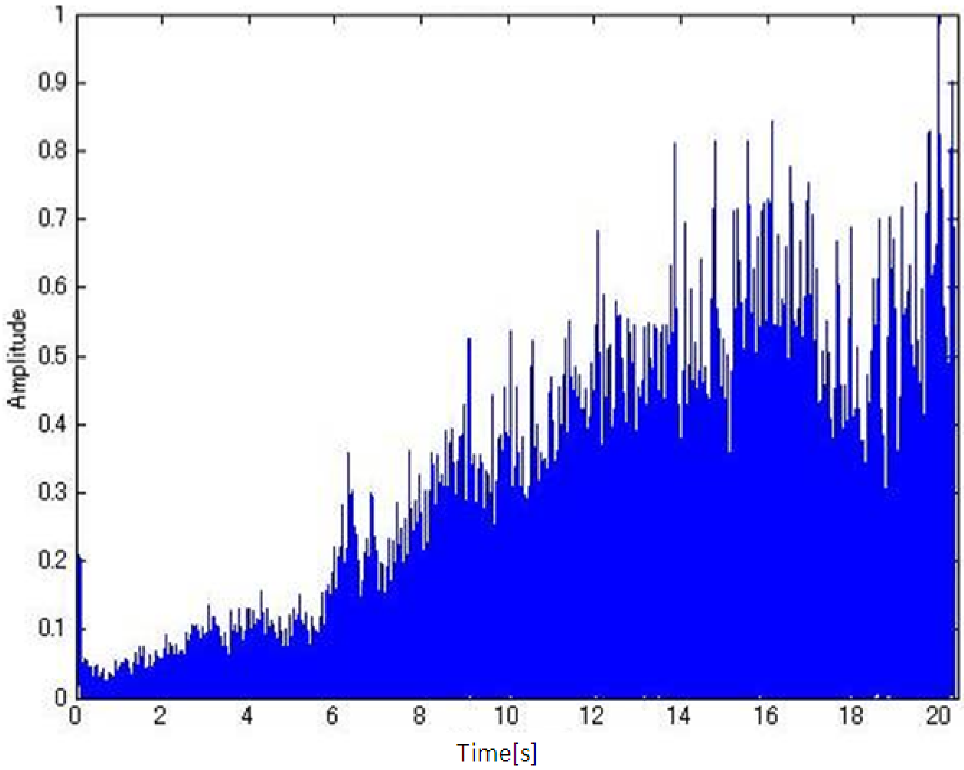


FIGURE 12. Difference of $c(n)$ and $e(n)$

In the results of the data analysis, the spectrum interpolation increased the sport factor score. The elimination of a half-harmonic and the second harmonic also increased the sport factor score. Spectrum interpolation increased the luxury factor score. The elimination of a half-harmonic also increased the luxury factor score. However, the elimination of the second harmonic reduced the luxury factor score. The reason for this is that the elimination of the second harmonic produced a lighter sound. A half-order in the car engine sound decreased both the sporty feeling and luxury factor. Further, a reduction in the spectrum power also decreased the sporty feeling and luxury factor score. The elimination of the second-order component of the car engine sound also improved the sporty feeling. Therefore, adjusting the spectrum power level can change the impression of the car engine sound. Thus, the engine sound impression can be improved using ANC.

Finally, to change the car engine noise to a desired sound, we applied the command filtered-x LMS algorithm to an actual car interior noise. The harmonic structure of the car interior noise can be observed more clearly when controlled by the command filtered-x LMS algorithm. However, the overall control performance was insufficient. This insufficiency occurs because the disturbances increase when the engine speed increases; further, the noise frequency increases. As the engine speed increased, the errors increased, and at speeds greater than 5000 rpm, these errors increased remarkably. Consequently, the necessity to provide countermeasures to address the disturbance caused is indicated.

In future work, the above findings will be adapted to actual sound design in vehicles and will be used in quality control techniques to improve the robustness to disturbances.

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