Adaptive Feedback Canceller with Howling Detection for Hearing Aids

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***Abstract*—Howling is a very annoying problem to hearing aid users because it restricts the maximum gain of a desired signal to the hearing aid users. In general, howling can be eliminated by using an adaptive feedback canceller which estimates the feedback path from the loudspeaker to the microphone equiped in the hearing aid. When the desired signal is a correlation signal, the feedback canceller often degrades the speech quality which is called as entrainment. To prevent the generation of the entrainment, an adaptive feedback canceller with prediction error filter has been proposed. Since the prediction error filter removes the correlation components from the desired signal, this feedback canceller works for the uncorrelated signal and the entrainment does not occur. Unfortunately, the prediction error filter gives only zeros when the desired signal is a periodic signal. In this case, howling cannot be eliminated because howling is also periodic. In this paper, we propose a feedback canceller that switches two conventional systems, where one eliminates howling and the other eliminates entrainment. The key technology of the proposed method is howling detection which utilizes saturation characteristics of the observed signal. Simulation results show that the proposed method works effectively to cancel both howling and entrainment in comparison to the conventional methods.**

I. Introduction

Howling is a common problem in hearing aids. It is a very annoying problem to the hearing aid users because the maximum usable gain of a desired signal is limited. In hearing aids, a closed-loop is formed by a leakage signal from the loudspeaker to the microphone, where the leakage signal is referred to a feedback signal [1]. The howling occurs when the gain in the closed-loop is larger than unit. Unfortunately, hearing aids are easy to produce the howling because the microphone is located at close to the loudspeaker, and hearing aids require the gain greater than unit. Generally, an adaptive feedback canceller (AFC) is used in hearing aids to remove the howling [2]. Since the feedback path is time-varying, the AFC adaptively estimates the feedback path and removes the feedback signal by subtracting the replica of the feedback signal from the observed signal. The difference between the replica and the observed signal gives an estimation error. The AFC works to minimize the mean square value of the estimation error. When a reference signal input to the AFC is uncorrelated with the observed signal, the feedback signal is successfully removed by the AFC. On the other hand, when the reference signal is correlated with the observed signal, the AFC estimates both the feedback path and the correlation component. In this case, the desired signal may be distorted due to reduction of its auto-correlation. The distortion is called as entrainment [3] [4]. To prevent the generation of the entrainment, the prediction error method-based adaptive feedback canceller (PEM-AFC) has been proposed [5]. The PEM-AFC is an entrainment free system under the assumption that a desired signal is an AR process generated from a white noise. The PEM-AFC uses a prediction error filter to produce an uncorrelated signal which is used to estimate the feedback path. The PEM-AFC eliminates both the howling and the entrainment while the assumption is satisfied. Unfortunately, this assumption is not satisfied for periodic signals. When the desired signal is a periodic signal, the prediction error filter gives only zeros. It means that the PEM-AFC loses the estimation ability for the feedback path. In this case, the PEM-AFC cannot eliminate the howling because the howling is also a periodic signal.

In this paper, we propose a howling canceller that eliminates both the howling and the entrainment even if the desired signal is periodic. The proposed method employs the PEM-AFC, a traditional AFC (T-AFC), and a howling detector. When the howling is detected, the proposed method switches from the PEM-AFC to the T-AFC in order to eliminate the howling. After eliminated the howling, the proposed method switches from the T-AFC to the PEM-AFC, to avoid the entrainment. In the proposed method, the howling detection is the most important technology. Since howling is resonance phenomenon, thus the output signal from the hearing aid is immediately saturated and the saturation is repeated. On the other hand, the desired signal is often saturated when the hearing aid user sets a large gain of the observed signal, i.e., this saturated signal should be produced. We call such saturated desired signal as SD signal (Saturated Desired signal). We have to distinguish the howling from the SD signal when the output signal is saturating. When the SD signal is a periodic signal, it is difficult to distinguish the howling from the SD signal. Thus, an exact detection of the howling is a challenging task.

When the feedback signal is completely canceled, the howling disappears, while the SD signal remains. Hence, we can detect the howling when the observed signal becomes extremely small by stopping the output signal of the hearing aid. However, while stopping the output signal, the SD signal is also stopped. To avoid the degradation about the SD signal, we should detect the SD signal without stopping the output signal. It is a challenging task. Here, only in a clear case, we establish a SD signal detection method without stopping the output signal. While the howling repeats the saturation, the SD signal does not guarantee to repeat the saturation, especially when the desired signal is a speech signal which can be modeled as a super Gaussian process so that the signal mainly takes zero or a small value and often takes a large value [6]. Hence, we assume that the saturation caused from the SD signal sparsely arises in comparison to the howling-based saturation. The SD signal detection can be achieved by counting a saturating time included in a certain analysis time, i.e., a short saturating time denotes the SD signal. When we have a long saturating time, we stop the output signal to detect the SD signal or the howling. Simulation results show that the proposed method with the howling detection is superior to the conventional methods.

This paper is organized as follows. In Section II, we explain about the T-AFC and the PEM-AFC. Section III proposes the method that eliminates both the howling and the entrainment for any observed signals. After that, we show that the capability of the proposed method is superior to that of the coventional methods in Section IV. In Section V, we conclude this research.

II. Conventional Feedback Cancellers

This section introduces two conventional feedback cancellers. We firstly explain about the T-AFC which effectively reduces the howling. Then, the PEM-AFC is explained, which is established to remove the entrainment.

Fig. 1 shows the block diagram of the T-AFC [2]. Here, $F(z)$ denotes the feedback path from the loudspeaker to the microphone and $G(z)$ denotes the signal processing path of the hearing aid. The transfer function of the adaptive digital filter (ADF) is denoted by $\hat{F}(z)$. The desired signal, the output signal and the feedback signal at time n are $x(n)$, $y(n)$ and $d(n)$, respectively. The observed signal is represented as $u(n) = x(n) + d(n)$. The reference signal to $\hat{F}(z)$, the replica of $d(n)$ and the estimation error signal are denoted by $r(n)$, $\hat{d}(n)$ and $e(n)$, respectively. When $\hat{F}(z)$ identifies $F(z)$, $e(n)$ is identical to $x(n)$, that is an ideal situation. Using an adaptive algorithm, e.g., the normalized least mean square (NLMS) algorithm [7], to update $\hat{F}(z)$, $e(n)$ approximates $x(n)$ when $r(n)$ is uncorrelated with $x(n)$. Note that $F(z)$ has a delay, thus $d(n)$ is uncorrelated with $x(n)$ if $x(n)$ is a white noise. In the case of that $x(n)$ and $r(n)$ are correlated, $\hat{F}(z)$ estimates both $F(z)$ and the correlation component between $x(n)$ and $r(n)$. Then, $r(n)$ becomes uncorrelated with $x(n)$. In the case of that $x(n)$ and $r(n)$ are uncorrelated, $\hat{d}(n)$ becomes zero. Then, $r(n)$ becomes correlated with $x(n)$ again. The repetition of the above procedure causes the entrainment.

To prevent the generation of the entrainment, the PEM-AFC has been proposed [5]. The block diagram of the PEM-AFC is shown in Fig. 2. Here, $A(z)$ denotes an AR model, which

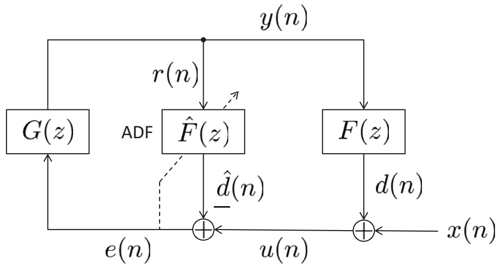


Fig. 1: Block diagram of T-AFC

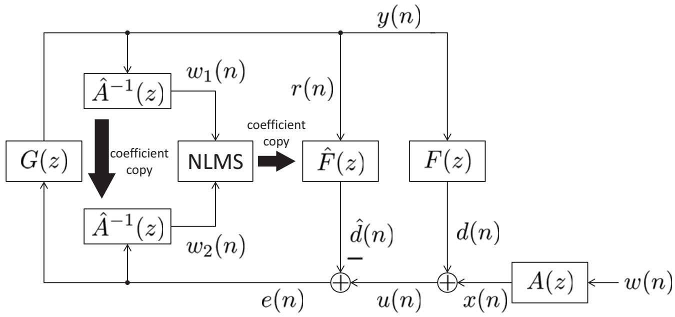


Fig. 2: Block diagram of PEM-AFC

is inversely stable, represented as

$$A(z) = \frac{1}{1 + a_1 z^{-1} + \cdots + a_P z^{-P}}, \tag{1}$$

where P is the filter order and $a_1, \cdots, a_P$ are filter coefficients of $A(z)$. Then, we have

$$x(n) = -a_1 x(n-1) - \cdots - a_P x(n-P). \tag{2}$$

Because $A(z)$ is the AR model, $A^{-1}(z)$ is corresponding to a prediction error filter. Hence, we use a prediction error filter to estimate $A^{-1}(z)$. In Fig. 2, the upper $\hat{A}^{-1}(z)$ represents the transfer function of the prediction error filter which estimates $A^{-1}(z)$. The lower $\hat{A}^{-1}(z)$ has the same property to the upper $\hat{A}^{-1}(z)$. The upper and lower $\hat{A}^{-1}(z)$s provide $w_1(n)$ and $w_2(n)$, respectively. Because $w_1(n)$ becomes a white noise, $w_2(n)$ includes the signal by passing the white noise through $F(z)$. Thus, NLMS algorithm updates the filter coefficients of $\hat{F}(z)$, where the reference signal is $w_1(n)$ and the estimation error signal is $w_2(n)$. The PEM-AFC works for the uncorrelated signal to estimate $F(z)$ and does not produce an entrainment.

III. Adaptive Feedback Canceller with Howling Detection

The PEM-AFC assumes that $w_1(n)$ becomes a white noise. This assumption is not satisfied for periodic signals. Certainly, $w_1(n)$ becomes zero for periodic signals, and then $\hat{F}(z)$ is not updated. Because howling is also a periodic signal, $\hat{F}(z)$ cannot remove the howling. Thus, the PEM-AFC can remove the entrainment, but may not remove the howling. On the other hand, the T-AFC can remove the howling, but often causes the entrainment.

In the proposed method, when the howling is detected, the system is switched from the PEM-AFC to the T-AFC in order to eliminate the howling. After the T-AFC eliminates the howling, the proposed method switches from the T-AFC to the PEM-AFC in order to avoid the entrainment. In the proposed method, the howling detection is the most important factor. We utilize the difference between the howling and the SD signal, and derive the howling detector.

The howling occurs due to the closed-loop, and the SD signal occurs due to the large gain of the desired signal. In a saturating situation, putting $y(n) = 0$ forcibly eliminates the howling because the feedback signal is disappeared. By contrast, in the case of the SD signal, the observed signal remains even if $y(n) = 0$. Hence, we can detect the howling by using a binary parameter $h(n)$ given as

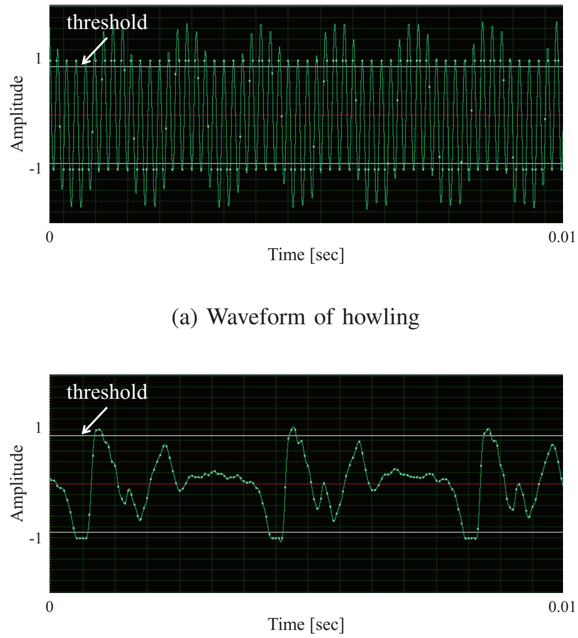
$$h(n) = \begin{cases} 1, & P(n) \leq T_p \\ 0, & P(n) > T_p \end{cases}, \tag{3}$$

$$P(n) = \sum_{m=0}^{t_{\text{stop}}-1} u^2(n-m), \tag{4}$$

where t_{stop} is the length of the analysis frame. When $P(n)$ becomes less than or equal to the threshold T_p, we have $h(n) = 1$ that denotes the howling. On the other hand, when $P(n)$ is greater than T_p, we have $h(n) = 0$ that can be considered as the SD signal. Thus, when $P(n) \leq T_p$, the proposed method produces $y(n)$ again and switches from the PEM-AFC to the T-AFC in order to remove the howling. After the T-AFC eliminates the howling, the proposed method switches from the T-AFC to the PEM-AFC in order to avoid the entrainment. On the other hand, when $P(n) > T_p$, $y(n)$ is produced again without switching. Unfortunately, in the case of the SD signal, it may repeat stopping and providing the output signal, and then an unpleasant noise causes.

As stated above, the proposed method can distinguish the howling from the SD signal at an expense of the degradation of the SD signal. We discuss the method that distinguishes the SD signal from the howling without the degradation about the SD signal. We focus on a difference of the output waveforms between the howling and the SD signal. The waveforms of the howling and the SD signal are depicted in Fig. 3 (a) and (b), respectively. Fig. 3 (a) shows that the howling repeats the saturation, and (b) shows that the SD signal sparsely casues the saturation. Thus, the SD signal can be distinguished by counting a saturating time included in a certain analysis time. Here, we define the ratio of the saturation time to the analysis time as

$$S(n) = \frac{1}{N} \sum_{l=0}^{N-1} \sigma(n-l) \tag{5}$$



(a) Waveform of howling

(b) Waveform of SD signal

Fig. 3: Saturation waveform of howling and SD signal

with

$$\sigma(n) = \begin{cases} 1, & |y(n)| > \alpha \\ 0, & \text{otherwise}, \end{cases},$$

where N is the number of samples for the analysis time and α is the threshold. The proposed method detects the SD signal by using a binary parameter given as

$$\tilde{h}(n) = \begin{cases} 0, & S(n) \leq T_s \\ 1, & S(n) > T_s \end{cases}. \tag{6}$$

When $S(n) \leq T_s$, we have $\tilde{h}(n) = 0$ and it means that the signal is a SD signal. Then, the proposed method does not stop the output signal. When $S(n) > T_s$, the proposed method stops $y(n)$ and distinguishes the howling from the SD signal by using (3). Thus, introducing (6), we can reduce the degradation of the SD signal. Here, the processing time to distinguish the howling from the SD signal is $N + t_{\text{stop}}$.

The flow of the proposed method is shown in Fig. 4. The block diagram of the proposed method is illustrated in Fig. 5. The signal $\tilde{y}(n)$ denotes the amplified signal by $G(z)$. In Fig. 5, selecting branch 1 gives the PEM-AFC and selecting branch 2 gives the T-AFC. Usually, we put $y(n) = \tilde{y}(n)$ and select the branch 1. When $\tilde{h}(n) = 1$, we put $y(n) = 0$ and calculate (3). When $h(n) = 1$, we put $y(n) = \tilde{y}(n)$ and select the branch 2 to eliminate the howling.

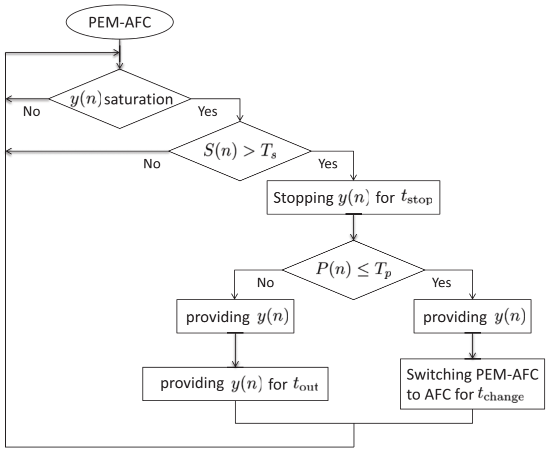


Fig. 4: Flow of proposed method

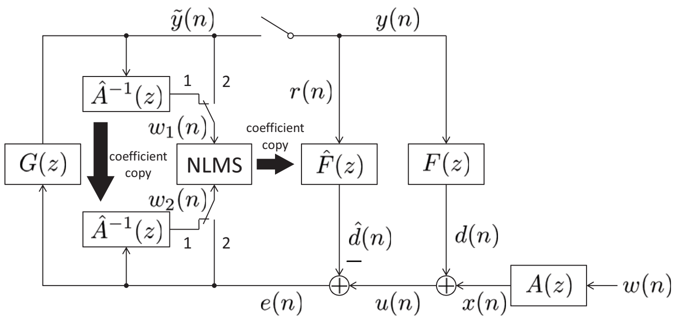
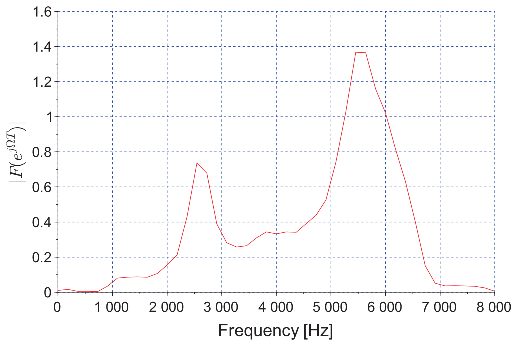


Fig. 5: Block diagram of the proposed method

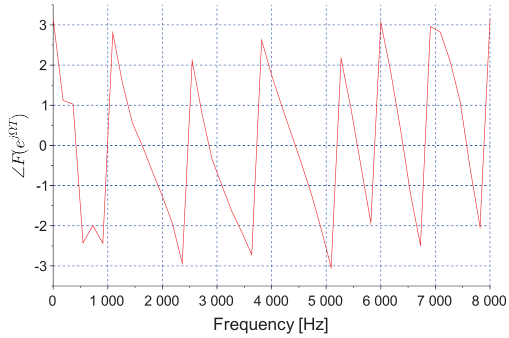
IV. Simulation

A. Conditions

In this section, we compare the capabilities of the proposed method with the conventional T-AFC and PEM-AFC. In the simulation, we use speech signals and some periodic signals, e.g., sinusoid, back buzzer of a vehicle, orin and chime, as $x(n)$. All signals are sampled at 16000 Hz. We put the parameters of the proposed method as $N = 1600$, $\alpha = 0.9$, $T_s = 0.9$, $t_{\mathrm{stop}} = 0.01$ sec, $t_{\mathrm{change}} = 0.5$ sec, $t_{\mathrm{out}} = 1.0$ sec and $T_p = 0.01$ in an empirical manner. The NLMS algorithm was used to update $\hat{F}(z)$, where we empirically put the step size as 0.2 for the T-AFC and 0.0001 for the PEM-AFC, respectively. In the simulations, to confirm the howling elimination capability, $\hat{F}(z)$ is initialized at a certain time index. In the PEM-AFC, the prediction error filter $\hat{A}^{-1}(z)$ is updated by the Burg lattice algorithm [5]. We put $G(z) = Kz^{-D}$ with $D = 120$ and $K = 10^{\frac{5}{4}}$. For the back buzzer of a vehicle, we put $D = 120$ and $K = 10$. These K values were put to absolutely generate the SD signal in the simulation. The feedback path $F(z)$ is a FIR filter with filter length $L = 89$ obtained from a measured practical feedback path. The frequency characteristic of $F(z)$ is depicted in Fig. 6, where (a) shows the amplitude characteristics. The amplitude spectrum is largely beyond unit around 5500 Hz. Fig. 6 (b) shows the phase characteristic where the phase spectrum equals to zero around 5500 Hz. Thus, the howling will occur around 5500 Hz. To evaluate the capabilities of the howling cancellers, we used SNR (Signal to Noise Ratio) given as



(a) Amplitude characteristic



(b) Phase characteristic

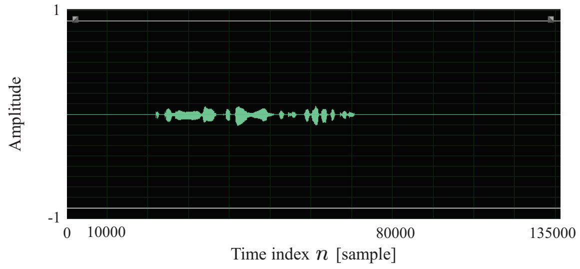
Fig. 6: Frequency characteristic of $F(z)$

$$\mathrm{SNR} = 10\log_{10}\frac{\sum_n (x(n))^2}{\sum_n (x(n) - e(n))^2}. \tag{7}$$

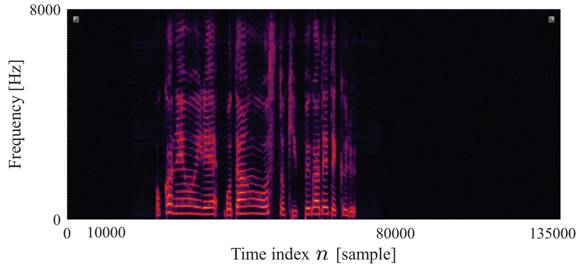
As an example, the waveform and the spectrogram of the speech signal used in the simulation are shown in Fig. 7 (a) and (b), respectively. The speech signal exists from about 20000 to 75000 samples, and it has harmonic components in many segments. As other example, the waveform and the spectrogram of the back buzzer of a vehicle are shown in Fig. 8 (a) and (b), respectively. The sound exists also from about 20000 to 75000 samples. From Fig. 8 (b), we see that the back buzzer has complete harmonic components which are 2000, 4000 and 6000 Hz. This shows that the back buzzer is a periodic signal.

B. Simulation Results

The waveform and the spectrogram of the simulation results for the speech signal in the T-AFC are shown in Fig. 9 (a)

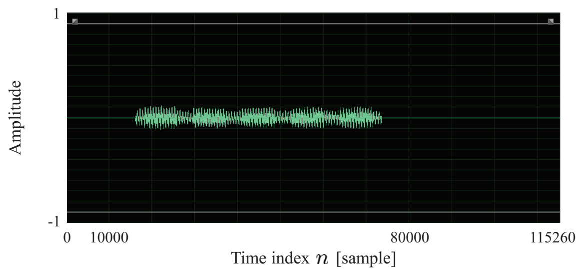


(a) Waveform

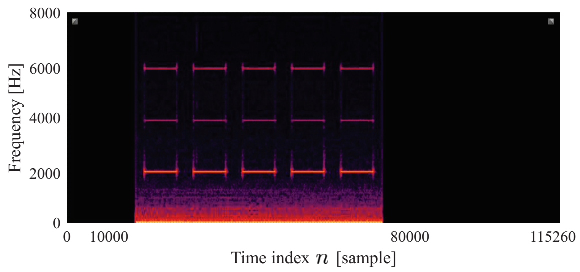


(b) Spectrogram

Fig. 7: Desired speech signal $x(n)$



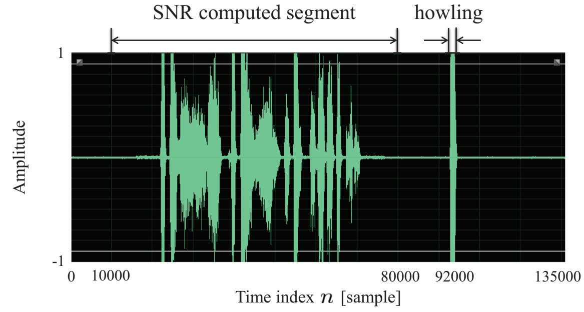
(a) Waveform



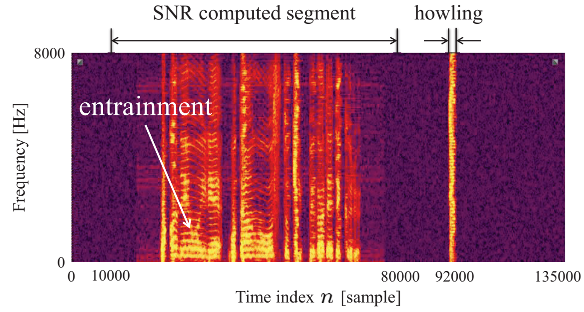
(b) Spectrogram

Fig. 8: Desired back buzzer of a vehicle $x(n)$

and (b), respectively. Fig. 9 (a) shows that the T-AFC causes the howling at $n = 92000$ which is the time index of the initialization of $\hat{F}(z)$. The T-AFC eliminates the howling in a short time. However, Fig. 9 (b) shows that the T-AFC causes the entrainment in speech signal segments. The waveform and the spectrogram of the simulation results in the PEM-AFC are shown in Fig. 10 (a) and (b), respectively. Fig. 10 (a)



(a) Waveform

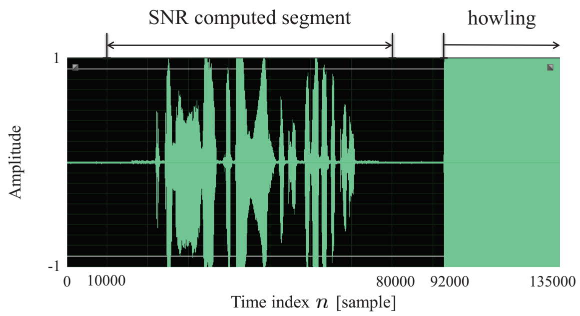


(b) Spectrogram

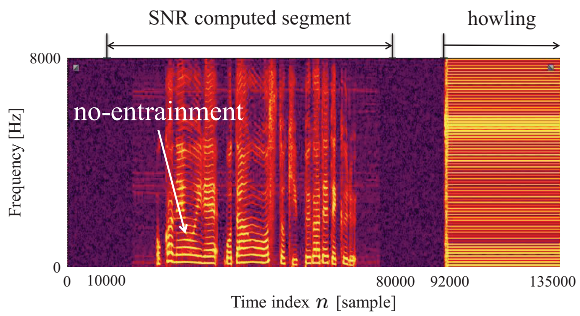
Fig. 9: T-AFC output signal for speech signal

shows that the PEM-AFC cannot remove the howling caused at $n = 92000$. However, Fig. 10 (b) shows that the PEM-AFC does not cause the entrainment. The simulation results in the proposed method are shown in Fig. 11 (a) and (b), respectively. Fig. 11 (a) shows that the proposed method removes the howling caused at $n = 92000$, in a short time. Furthermore, Fig. 11 (b) shows that it does not cause the entrainment. However, to remove the howling, the proposed method has to take a time slightly longer than the T-AFC, because the proposed method needs the time to distinguish the howling from the SD signal. The required time to remove the howling is about 0.5 sec in the proposed method.

On the other hand, for the back buzzer, the waveform and the spectrogram of the simulation results in the T-AFC are shown in Fig. 12 (a) and (b), respectively. Fig. 12 (a) shows that the T-AFC causes the howling at $n = 101000$ which is the time index of the initialization of $\hat{F}(z)$. We see that the PEM-AFC eliminates the howling in a short time. However, Fig. 12 (b) shows that the T-AFC causes the entrainment. The simulation results of the PEM-AFC are shown in Fig. 13 (a) and (b), respectively. Although Fig. 13 (a) shows that the PEM-AFC cannot remove the howling, we see from (b) that the PEM-AFC does not cause the entrainment. Finally, the simulation results of the proposed method are shown in Fig. 14 (a) and (b), respectively. Fig. 14 (a) shows that the proposed method removes the howling, and (b) shows that it does not cause the entrainment. We see from these results that the proposed method can effectively use the advantages

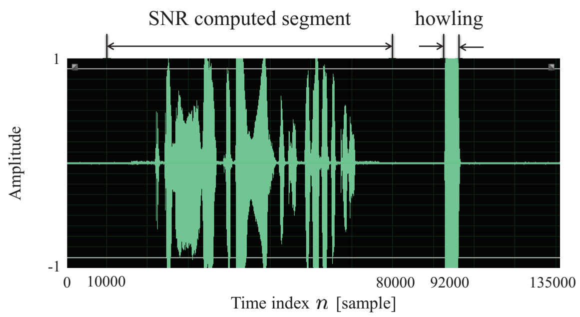


(a) Waveform

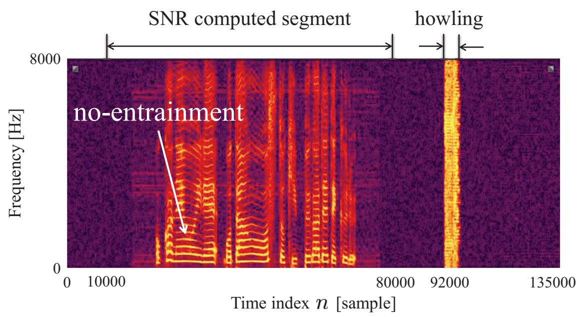


(b) Spectrogram

Fig. 10: PEM-AFC output signal for speech signal

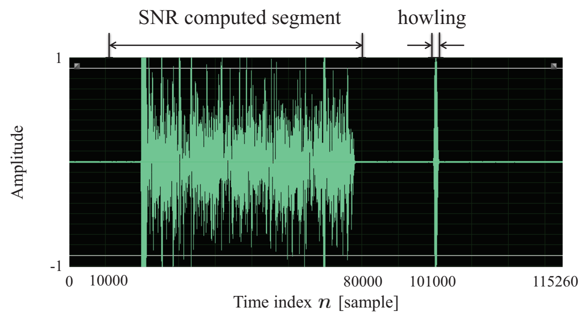


(a) Waveform

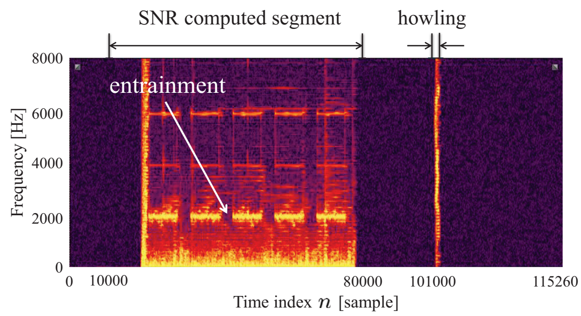


(b) Spectrogram

Fig. 11: Proposed method output signal for speech signal



(a) Waveform



(b) Spectrogram

Fig. 12: T-AFC output signal for back buzzer of vehicle

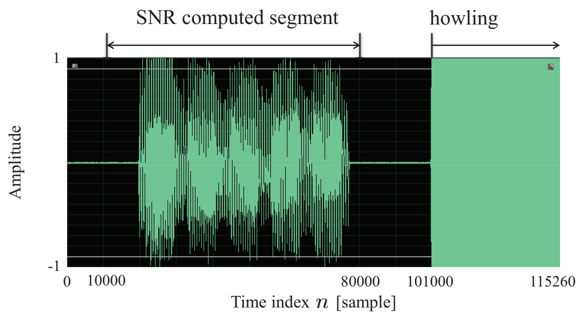
TABLE I: SNR [dB]

$x(n)$	T-AFC	PEM-AFC	proposed method
speech signal	-2.7	35.5	38.2
other speech signal	-1.9	39.5	41.2
sinusoid	-20.3	15.4	15.3
back buzzer of vehicle	-8.4	17.3	22.6
orin	-6.6	35.7	37.2
chime	-9.1	29.8	32.1

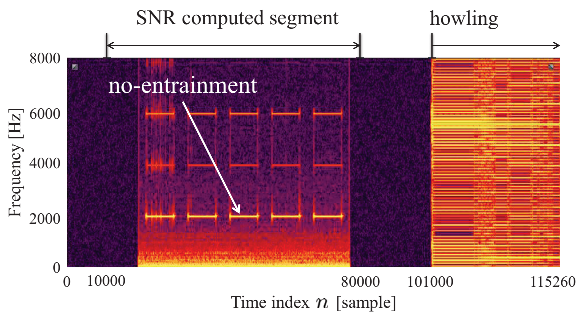
of these two conventional methods.

Table I shows SNR results, where SNR is computed for evaluating the sound quality, specifically the computation was done within $10000 \leq n \leq 80000$. From these results, we see that SNRs of the T-AFC are extremely less than that of the PEM-AFC and the proposed method for all desired signals. This main reason is that the T-AFC caused the entrainment. On the other hand, SNRs of the proposed method are almost the same or slightly improved in comparison to the PEM-AFC for all signals, although the PEM-AFC could not remove the howling as shown in Figs. 10 and 13. The results show that the proposed method gave the best performance to eliminate both the howling and the entrainment in comparison to the conventional methods.

Table II shows the processing time to remove the howling when the desired signal is the speech shown in Fig. 7. The PEM-AFC cannot remove the howling. The proposed method takes about twice as long as the T-AFC. The improvement of the processing time to remove the howling is included in out future works.

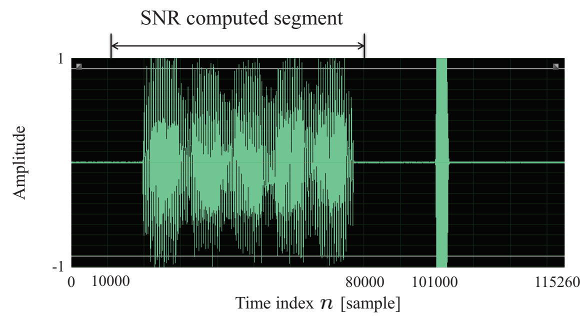


(a) Waveform

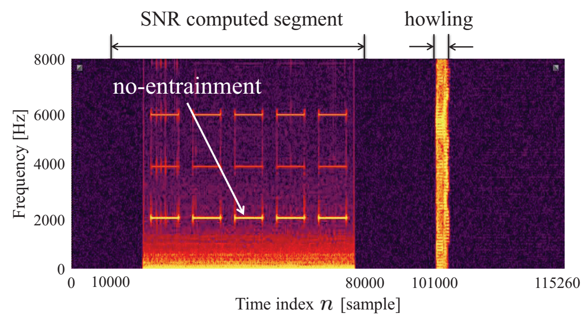


(b) Spectrogram

Fig. 13: PEM-AFC output signal for back buzzer of vehicle



(a) Waveform



(b) Spectrogram

Fig. 14: Proposed method output signal for back buzzer of vehicle

TABLE II: Processing time to remove howling [samples]

T-AFC	PEM-AFC	proposed method
2000	∞	3900

V. Conclusions

In this paper, we proposed the howling canceller that switches two coventional systems to eliminate both the howling and the entrainment. Since the proposed system requires a howling detector, we developed the howling detection method based on the difference between the respective saturating signals caused from the howling and the SD signal. The simulation results showed that the proposed method did not produce the entrainment and removed the howling within 0.5 sec even if the desired signal is periodic.

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