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Performance analysis of an adaptive feedback active noise control based earmuffs system

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ABSTRACT

This paper analyzes the performance of the adaptive feedback active noise control (FBANC) based earmuffs system. The system's noise reduction performance is obtained in a closed-form equation with respect to two top-level design constraining parameters, i.e., secondary path delay and noise bandwidth. To derive the equation, we utilize a simplified and equivalent linear prediction ANC model and parameterize noise bandwidth using an autoregressive model. The derived equation is validated by simulations and experimental tests performed for the ANC earmuff system. The high degrees of noise reduction, which are 14.9 dB for the airplane noise and 20.4 dB for the house heater noise, obtained from the experimental tests confirm the feasibility of the ANC earmuffs application.

1. Introduction

Active noise control (ANC) earmuffs are intended to suppress the external noises whose dominant components are at relatively low frequency band, such as airplane engine noise, rotating machine noises in plants, house heater noise, etc. [1–4]. Passive earmuffs alone are ineffective to suppress the noise components at the frequency range below several hundred Hertz and tend to be very expensive and bulky [5–7].

Many commercial ANC headsets applications are developed based on the feedforward ANC scheme. However, the feedforward ANC systems for headsets have significant stability and performance deficiencies caused by nonstationary reference inputs, measurement noise, and acoustic feedback [1,6,8–10]. Unlike the feedforward ANC, the adaptive feedback active noise control(FBANC) provides a more accurate noise cancelation since the microphone is placed inside the ear-cup of the headset [10]. The functional structure of the FBANC earmuffs system is illustrated in Fig. 1.

Most of previous works performed in regards to the feedback ANC architecture are the transfer-function-model-based approaches to address the stability, sensitivity and robustness issues of the system [11–14]. In general, the model-based approaches do not directly provide explicit and geometric interpretations in the domain of physical parameters, such as geometric parameters of noise canceling space, electro-acoustic coupling delay, noise characteristics parameters, etc. On the other hand, most of previous works addressing the explicit effects of physical parameters rely on, instead of an analytic approach, direct simulations to show the effects in the noise reduction of the ANC system [13–15].

In this paper, two key physical parameters of FBANC, i.e., secondary path delay and noise bandwidth, are selected and their combined effects are analytically investigated to obtain a closed-form noise reduction equation.

The secondary path is named for the electro-acoustic coupling between the speaker system and the sensing microphone system. The delay in the secondary path significantly degrades the noise reduction performance of the ANC system. Therefore there exists a tradeoff between the noise reduction performance and the size of spatial coverage range of noise canceling [13,16]. The performance degradation becomes significantly aggravated when the delay becomes longer than the coherence-time of noise correlation. The coherence time is inversely proportional to the noise bandwidth. Therefore, it is very meaningful to investigate the combined effect of secondary path delay and noise bandwidth on the performance degradation of the FBANC earmuffs system.

In order to demonstrate the exclusive effects of aforementioned two parameters, a simplified and equivalent Δ-step linear predictor model of the FBANC system is used for the performance analysis of

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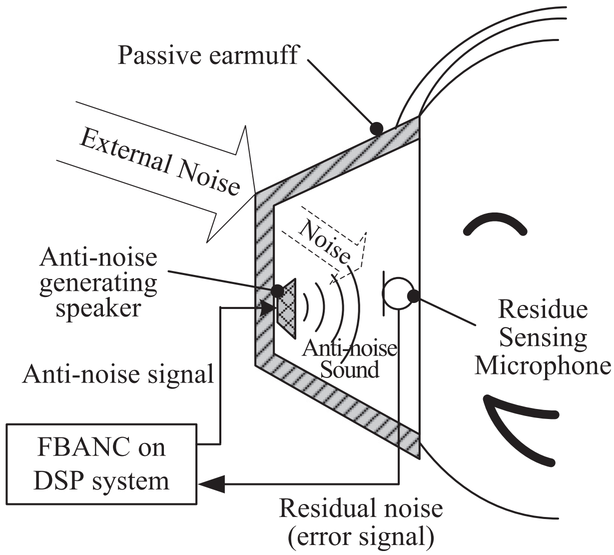

Fig. 1. Functional structure of an ANC earmuffs system.

the FBANC. The explicit inclusion of the delay as the structural parameter of the predictor model, i.e., the model's Δ-step prediction distance, enables a straightforward derivation of the exclusive effect of the delay on the performance degradation. The noise bandwidth is parameterized using the second order autoregressive model and applied to the linear predictor model for deriving a closed-form noise reduction equation. This approach provides a useful result in the sense that two key design and application constraining parameters, i.e., secondary path delay and noise bandwidth, are explicitly included in the closed-form equation showing their combined effects.

Computer simulations and experimental tests are performed to verify the analytic derivation of the noise reduction performance regarding the FBANC earmuffs system. Recorded airplane noise and house heater noise are also used as the primary noise in the tests to show the applicability of the analysis.

2. Derivation of noise reduction performance of the adaptive feedback ANC based earmuffs system

This section is devoted to a derivation of noise reduction performance of the FBANC earmuffs system. In the derivation, the FBANC's equivalent linear predictor model and the autoregressive model based primary noises are used. In the following Sections 2.1 and 2.2, the overall procedures of the simplified derivation method and its derived result are presented respectively. In the Section 2.3, the overall effects of secondary path delay and noise bandwidth are shown with an exemplary illustration of performance curves.

2.1. Linear predictor model based performance derivation

This section describes the details of the linear predictor model based performance derivation. In the derivation, the feedback ANC is simplified to an equivalent Δ-step linear predictor with the assumption that the secondary path is a pure Δ-step delay and its estimation is errorless [1,6,9]. By exploiting the prediction error of the Δ-step linear predictor, the noise reduction performance of the ANC can be derived to examine the combined effect of the secondary path delay and the coherence time of the noise correlation.

A typical structure of the adaptive feedback ANC system is shown in Fig. 2. The FBANC system suppresses the primary noise $d(n)$ by generating the anti-noise $y(n)$ with the synthesized reference signal $x(n)$. The secondary path $S(z)$ represents the electro-acoustic coupling path from the loudspeaker to the error microphone. $\hat{S}(z)$ is the internal estimated model of $S(z)$, which is used for the estimation of primary noise $\tilde{d}(n)$.

The simplified Δ-step linear predictor model of the FBANC is obtained by assuming $S(z) = z^{-\Delta}$ and $\hat{S}(z) = S(z)$. The simplified model is shown in Fig. 3, where the order of $z^{-\Delta}$ and $W(z)$ can be changed under the assumption of quasi-stationarity of the primary noise. Such structural simplicity enables the straightforward derivation of the exclusive effect of the delay and the noise statistics. Even though the structure of the linear predictor model seems over-simplified, the utilization of the simplified model is justifiable considering that the disturbance of model parameters should be assumed to be controlled by the feedback mechanism and most of all, the use of a nominal plant model is reasonable for the purpose of performance bound analysis [6].

Since the model has an entirely feedforward structure, the theoretical maximum noise reduction (NR) bound can be readily derived in the sense of Wiener as

$$\mathrm{NR}_{\max} = \frac{E\left[|d(n)|^2\right]}{E\left[|e_{\min}(n)|^2\right]} = \frac{E\left[|d(n)|^2\right]}{E\left[|d(n) - \mathbf{w}_o^H \mathbf{x}(n)|^2\right]} = \frac{\sigma_d^2}{\sigma_d^2 - \mathbf{r}(-\Delta)^H \mathbf{R}^{-1} \mathbf{r}(-\Delta)} \qquad (1)$$

where $\mathbf{w}_o = \mathbf{R}^{-1}\mathbf{r}(-\Delta)$: the optimum filter coefficient vector,

$e_{\min}(n)$: the minimum prediction error,
$\mathbf{x}(n) = [d(n-\Delta) \quad d(n-\Delta-1) \quad \cdots \quad d(n-\Delta-M+1)]^T$,
$E[\cdot]$: expectation operator,
$E[d(n)] = 0$,
$\sigma_d^2 = E[d(n)d^*(n)]$,
$\mathbf{R} = E\left[\mathbf{x}(n)\mathbf{x}^H(n)\right]$,

$\mathbf{r}(-\Delta) = E[\mathbf{x}(n)d^*(n)] = [r(-\Delta) \quad r(-\Delta-1) \quad \cdots \quad r(-\Delta-M+1)]^T$.

The autocorrelation vector $\mathbf{r}(-\Delta)$ in (1) consists of the autocorrelations of the primary noise with the time lag from $-\Delta$ to $-(\Delta+M-1)$, which is the Δ-step predictor's filtering window duration.

Our motivation of investigating the combined effect of secondary path delay and noise bandwidth is based on (1), where the noise reduction determining factor $\mathbf{r}(-\Delta)$ depends on the relative length between the secondary path delay Δ and the effective time lag width of autocorrelation which is the inverse of the noise bandwidth. Specifically, the noise reduction performance

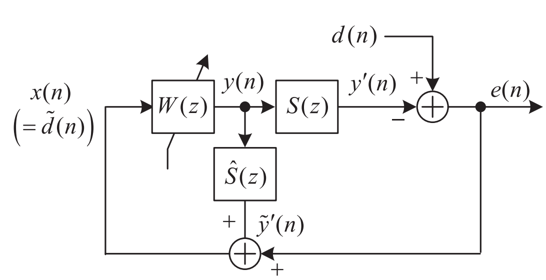

Fig. 2. Block diagram of a typical adaptive feedback ANC system.