Active Noise Control for Headrests

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***Abstract*—This paper presents the active noise control (ANC) systems for creating quiet zone to cover the users' ears in headrests. The two-input two-output (TITO) ANC headrest system based on the multiple-channel adaptive feedback filtered-x least mean square (FXLMS) algorithm is proposed. In order to reduce system cost of the TITO ANC headrest system, the combined-input combined-output (CICO) ANC headrest system based on the single-channel adaptive feedback FXLMS algorithm is developed. The performance of the proposed ANC headrest systems are evaluated using the experimental setups. The real-time experiment results show that the CICO ANC headrest system achieves the satisfactory performance.**

I. Introduction

Noise exists everywhere, such as in airplanes, bedrooms, public buildings and many others. Thus, when people sit on their seats, they may feel uncomfortable because of noise exposure. In general, people can wear ANC headsets [1] to reduce the noise exposure. However, it is still uncomfortable to wear this kind of device for a long period of time. In this paper, we develop ANC headrest systems (Fig. 1) mounted on the seats to create quiet zone around users' ears so that they can relax in quiet environment when they sit on these seats.

There are many difficulties in developing the ANC headrest systems for real applications. Since, the location of the headrest is in open air environment, the noise sources and characteristics are unknown in the design stage. Besides, the head can move, resulting in changing acoustic paths associated with the ANC system. Also, most headrests are limited in size that restricts the ANC hardware design. These factors add a lot of challenges in the ANC headrest system design.

Olson and May [2] suggested the principle of local ANC through development of an electronic sound absorber. The basic idea motivated many researchers to develop ANC headrest systems. Some works [3, 4] proposed ANC headrest systems using feedforward ANC technique with reference sensor. Although these papers reported that the noise reduction can be achieved, the feedforward ANC technique is not practice for practical applications since the noise sources are unknown. Rafaely and Elliott [5] proposed ANC headrest system using H2/H∞ feedback controller. They used two separate single input/single output systems, which needs double computation resources. Pawelczyk [6] developed multichannel feedback ANC algorithm for headrests. The

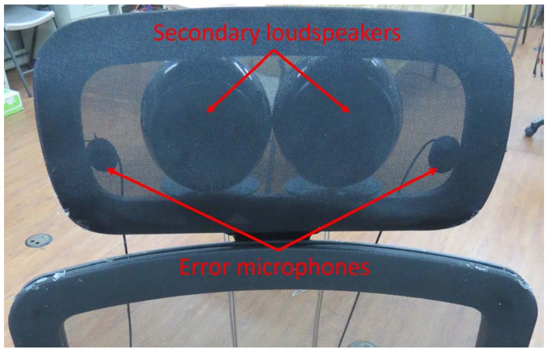


Fig. 1 Proposed ANC headrest system

headrest system achieved 20 dB of attenuation at the manikin's ear, but it required a large size of ANC system structure and four secondary loudspeakers.

This paper proposes the ANC headrest systems that meets realistic and practical implementation requirements. By using the adaptive feedback ANC (AFANC) algorithm, this system solves the challenge of unknown reference noise without using reference sensor. In this application, the quiet zone is required for both ears. Utilization of more secondary loudspeakers and error microphones can result in larger quiet zone [7]. In general, two secondary loudspeakers and two error microphones [8] are sufficient to create adequate size of quiet zone. However, it will increase computing and hardware cost. This paper proposes simplified algorithm to reduce the system cost and also investigates the size and characteristics of the quiet zone achieved around ear locations.

The rest of paper is organized as follows. Section II introduces the proposed ANC headrest system and the simplified system. Section III discusses different experimental setups based on the simplified structure. Section IV presents extensive real-time experiment results and the generated quiet zone performance. Section V presents the paper conclusion.

II. ANC Headrest Systems

A. Two-Channel ANC Headrest System

As shown in Fig. 2, the proposed ANC headrest system consists of two secondary loudspeakers (L_1 and L_2) and two error microphones (M_1 and M_2) mounted on the headrest. The ANC system generates the anti-noise signals $y_1(n)$ and $y_2(n)$ that drive the secondary loudspeakers to minimize the residual error signals $e_1(n)$ and $e_2(n)$ sensed by the error microphones. The ANC system creates two quiet zones around both ears.

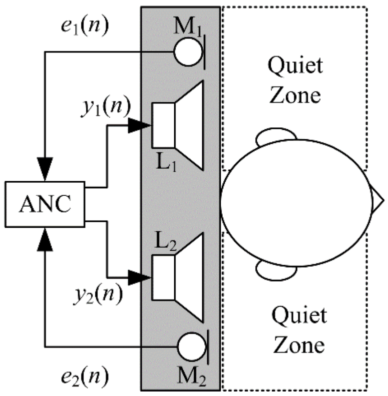


Fig. 2 Two-channel ANC headrest system

Based on the structure illustrated in Fig. 2, the two-input two-output (TITO) system based on the adaptive feedback 2x2 FXLMS algorithm [7] is developed, which is illustrated in Fig 3. This algorithm uses four adaptive filters to generate two secondary signals $y_1(n)$ and $y_2(n)$ expressed as

$$y_1(n) = \mathbf{w}_{11}^T(n)\mathbf{x}_1(n) + \mathbf{w}_{12}^T(n)\mathbf{x}_2(n) \quad (1)$$

$$y_2(n) = \mathbf{w}_{21}^T(n)\mathbf{x}_1(n) + \mathbf{w}_{22}^T(n)\mathbf{x}_2(n) \quad (2)$$

where $\mathbf{w}_{11}(n)$, $\mathbf{w}_{12}(n)$, $\mathbf{w}_{21}(n)$, and $\mathbf{w}_{22}(n)$ are the coefficient vectors of adaptive filters $W_{11}(z)$, $W_{12}(z)$, $W_{21}(z)$, and $W_{22}(z)$, respectively; $\mathbf{x}_1(n)$ and $\mathbf{x}_2(n)$ are reference signal vectors; and the superscript T denotes transpose operation.

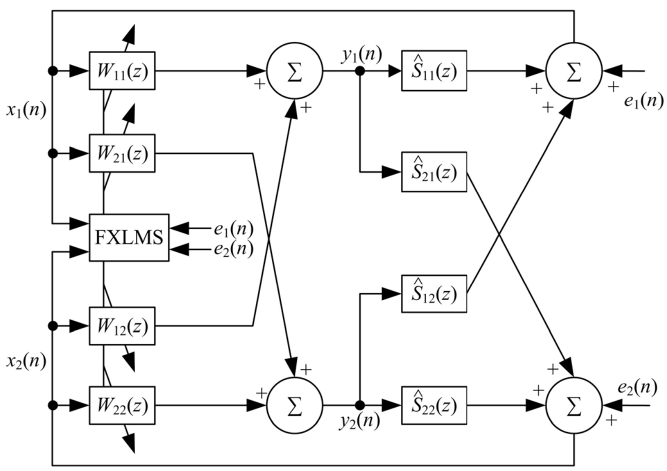


Fig. 3 Block diagram of the TITO ANC headrest system with the 2x2 FXLMS algorithm.

The reference signals $\mathrm{x}_1(n)$ and $\mathrm{x}_1(n)$ are synthesized as

$$\mathrm{x}_1(n) = e_1(n) + \hat{s}_{11}(n) * y_1(n) + \hat{s}_{12}(n) * y_2(n) \quad (3)$$

$$\mathrm{x}_2(n) = e_2(n) + \hat{s}_{21}(n) * y_1(n) + \hat{s}_{22}(n) * y_2(n) \quad (4)$$

The four fixed filters $\hat{S}_{11}(z)$, $\hat{S}_{21}(z)$, $\hat{S}_{12}(z)$, and $\hat{S}_{22}(z)$ are the estimates of secondary paths $S_{11}(z)$, $S_{21}(z)$, $S_{12}(z)$, and $S_{22}(z)$, respectively; where $S_{11}(z)$ is the secondary path from L_1 to M_1; $S_{21}(z)$ is from L_2 to M_1; $S_{12}(z)$ is from L_1 to M_2; and $S_{22}(z)$ is from L_2 to M_2. The 2x2 FXLMS algorithm for updating adaptive • lters is expressed as

$$\mathbf{w}_{11}(n+1) = \mathbf{w}_{11}(n) + \mu\{[\hat{s}_{11}(n) * \mathbf{x}_1(n)]e_1(n) + [\hat{s}_{21}(n) * \mathbf{x}_1(n)]e_2(n)\} \quad (5)$$

$$\mathbf{w}_{21}(n+1) = \mathbf{w}_{21}(n) + \mu\{[\hat{s}_{12}(n) * \mathbf{x}_1(n)]e_1(n) + [\hat{s}_{22}(n) * \mathbf{x}_1(n)]e_2(n)\} \quad (6)$$

$$\mathbf{w}_{12}(n+1) = \mathbf{w}_{12}(n) + \mu\{[\hat{s}_{11}(n) * \mathbf{x}_2(n)]e_1(n) + [\hat{s}_{21}(n) * \mathbf{x}_2(n)]e_2(n)\} \quad (7)$$

$$\mathbf{w}_{22}(n+1) = \mathbf{w}_{22}(n) + \mu\{[\hat{s}_{12}(n) * \mathbf{x}_2(n)]e_1(n) + [\hat{s}_{22}(n) * \mathbf{x}_2(n)]e_2(n)\} \quad (8)$$

where $\hat{s}_{11}(n)$, $\hat{s}_{21}(n)$, $\hat{s}_{12}(n)$, and $\hat{s}_{22}(n)$ are the impulse responses of the secondary-path estimates $\hat{S}_{11}(z)$, $\hat{S}_{21}(z)$, $\hat{S}_{12}(z)$, and $\hat{S}_{22}(z)$, respectively; * denotes linear convolution, μ is the step size that determines convergence rate and steady-state performance.

B. Single-Channel ANC Headrest System

This paper proposes the single-channel ANC headrest using two secondary loudspeakers connected as one (two loudspeakers are driven by the same anti-noise), and two error microphone combined as one analog input signal [9]. This proposed single-channel system is the combined-input combined-output (CICO) ANC headrest system based on the adaptive feedback 1x1 FXLMS algorithm, which is illustrated in Fig. 4.

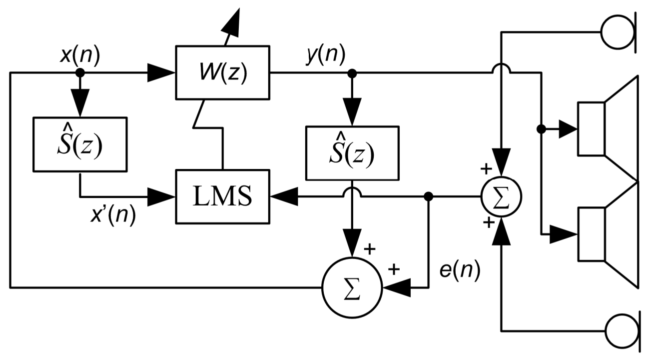


Fig. 4 Block diagram of the CICO ANC headrest system with the 1x1 FXLMS algorithm.

The purpose is to create a single quiet zone that covers both ears. Unlike the TITO ANC headrest system which controls two quiet zones using two anti-noise signals, the CICO ANC headrest system controls only one quiet zone using one anti-noise $y(n)$. One adaptive filters is used to generate the anti-noise signal expressed as

$$y(n) = \mathbf{w}^T(n)\boldsymbol{x}(n) \quad (9)$$

where $\mathbf{w}(n)$ is the coefficient vector of adaptive filters $W(z)$ and $\mathbf{x}(n)$ is reference signal vector. The fixed filter $\hat{S}(z)$ in Fig. 3 is the secondary-path estimate, from the mixed secondary loudspeakers to the combined of error microphones.

The 1x1 FXLMS algorithm for updating adaptive •lter is expressed as

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \mu[\hat{s}(n) * \mathbf{x}(n)]e(n) \qquad (10)$$

where $\hat{s}(n)$ is the impulse responses of the secondary-path estimates $\hat{S}(z)$ and μ is the step size.

The CICO ANC headrest system requires less computation and analog I/O channels than the TITO ANC headrest system as summarized in Table 1, where L is the length of the adaptive filter and M is the length of the estimated secondary path model. It shows that the CICO ANC headrest system is more efficient than the TITO ANC headrest system.

TABLE I
SUMMARY OF ANC CONFIGURATION

Structure Type		TITO	CICO
Num. of Loudspeaker		2	2
Num. of Microphone		2	2
Num. of Analog I/O Channel		4	2
Num. of Adaptive Filter		4	1
ANC Algorithm		2x2 FXLMS	1x1 FXLMS
Computation	Multiplication	$12L+12M+2$	$2L+2M+1$
	Addition	$12L+12(M-1)+2$	$2L+2(M-1)$

C. Hardware Design

The ANC headrest system was designed to fit into the real commercial headrest. Fig. 5 shows the geometrical arrangement of the proposed ANC headrest system. The headrest size is 32.5 x 16.5 cm^2. Two secondary loudspeakers (L_1 and L_2) are placed at the back of the headrest.

The desired locations for noise reduction are at user's ears. Therefore, the best locations of the error microphone is at user's ears location. However, it is not convenient to place the error microphone at that location. Theoretically, the 10 dB quiet zone [10] is created around the error microphone with the size of $\lambda/10$, where λ is the wavelength of desired noise. The lower the desired noise frequency, the larger quiet zone can be created. Therefore, the error microphone should be placed close to the ear.

On the other hand, the larger distance between secondary loudspeaker and microphone can help to obtain larger quiet zone [11]. Therefore, the secondary loudspeakers locations are chosen at the center of the headrest, while the error microphones (M_1 and M_2) locations are chosen at the end-side of the headrest. This arrangement provides the largest possible distance inside the headrest, while maintaining the close distant between the error microphones and ears.

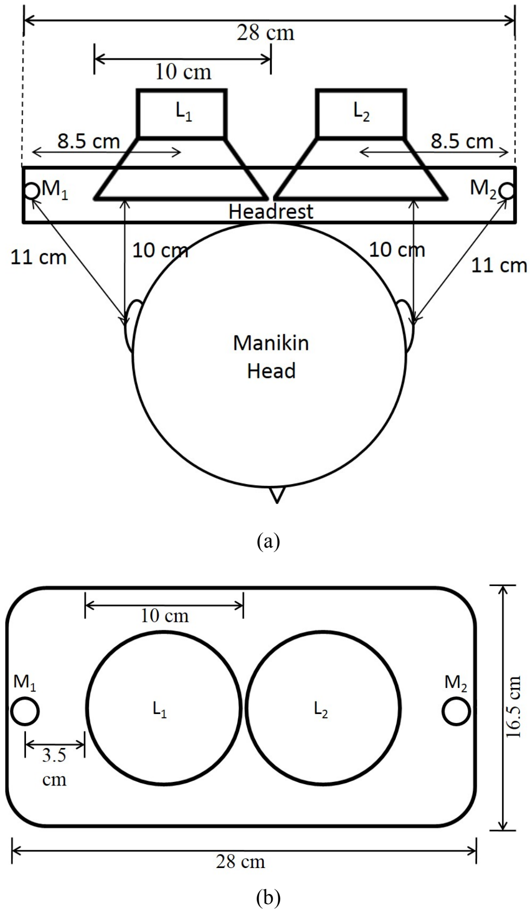


Fig. 5 Geometrical configuration of proposed systems. (a) top view, (b) front view

III. EXPERIMENTAL SETUPS

The performance of the proposed ANC headrest systems are evaluated by conducting real-time experiment using the experimental setup shown in Fig. 1. The experimental setup was built based on the design in Fig. 5. The experimental setup consists of two ORB® audio Mod1X spherical loudspeakers with diameter of 10.6 cm as the secondary loudspeakers. The power amplifier is Mod1X made by ORB® audio. Two Shure MX183 microphones were used as the error microphones with pre-amp from ALESIS®. The anti-aliasing and reconstruction filter were built from 8th order switched-capacitor filter with cut-off frequency set at 750 Hz.

A floating-point digital signal processor, TMS320C6713, was used to conduct the real-time experiments. The secondary paths were estimated using off-line modeling technique summarized in [7] with 124 finite impulse response (FIR) filter taps. The sampling frequency is 2 kHz. The noise was played by a primary loudspeaker located at 1 m of the back of the head. The ANC headrest system was placed in a laboratory. The head manikin was placed to act as user's head.

IV. Experiment Results and Analysis

Real-time experiments were conducted to evaluate the performance of quiet zone and practical noise reduction. Single tone with 300 Hz was used as testing noise to measure the quiet zone. Motorcycle noise was used to examine the performance of practical noise reduction.

A. Quiet Zone Performance

The quiet zone performance which is measured using the 3D measurement grid shown in Fig. 6. The measurement grid has measuring point at every 5.5 cm in x, y, and z axes. The measured data is shown in 2D plane after being interpolated with resolution of 0.1 cm using linear interpolation. The testing noise is single tone at 300 Hz. The noise reduction was calculated by measuring the different of noise level when ANC is on and off. All the points are measured and this paper presents only for z=19 cm, which is at around normal human ear level. The length of control filter was 150.

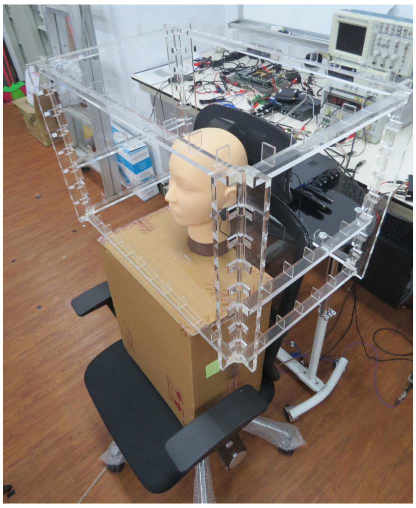
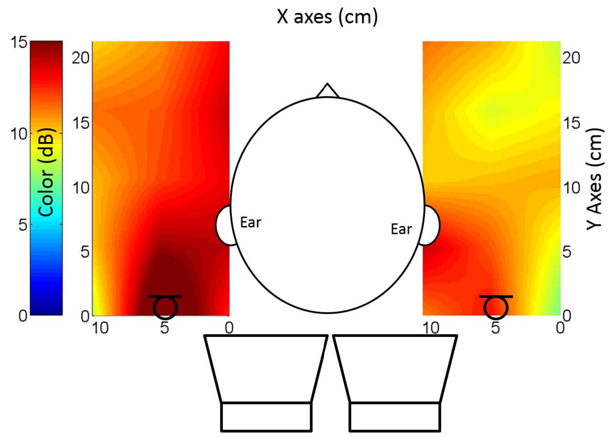


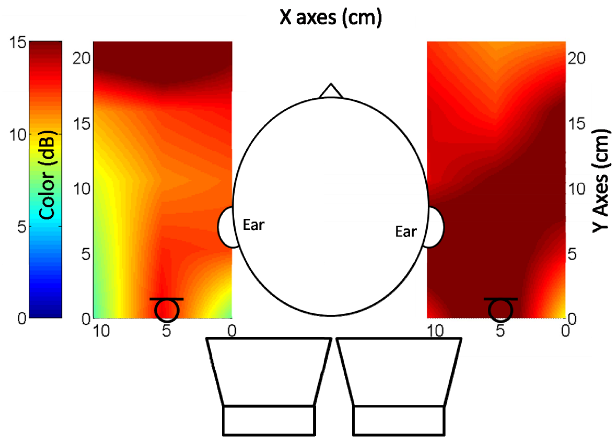
Fig. 6 Quiet zone measurement grid.

Theoretically, the size of 10 dB quiet zone has diameter of 11 cm near the error microphone because the testing noise is 300 Hz [10]. Fig. 7 shows the measured quiet zones at the left and right manikin's ears with the size of 10.6x21.2 cm^2 achieved by the TITO and CICO ANC headrest systems. The color shows the noise reduction in dB unit. Although the quiet zone is not distributed symmetrically because the measurement was not performed in anechoic chamber, it shows that the quiet zone size agrees with the theoretical calculation. The noise reduction is higher near the error microphone and is decreasing away from the error microphone.

Table 2 summarize the noise reduction achieved by the TITO and CICO ANC headrest systems. The TITO ANC headrest system achieved 11-12 dB noise reduction at the manikin's right ear location and 13-14 dB noise reduction at the manikin's left ear location. The CICO ANC headrest system achieved 15 dB noise reduction at the manikin's left ear location and 11-12 dB noise reduction at the manikin's right ear location.



(a)



(b)

Fig. 7 Quiet zone achieved by (a) TITO ANC headrest system, (b) CICO ANC headrest system.

Both ANC systems achieved 10 dB noise reduction at almost all the measured points. It means the proposed systems allows head movement in the area of 10.6x21.2 cm^2.

Based on the required computation (Table I), the TITO ANC headrest system requires 3290 multiplications and 3278 additions, while the CICO ANC headrest system requires 549 multiplications and 546 additions, which is almost six times less. The real-time experiment results prove that the CICO ANC headrest system is better than the TITO ANC headrest system based on factors of noise reduction and system cost.

Table II

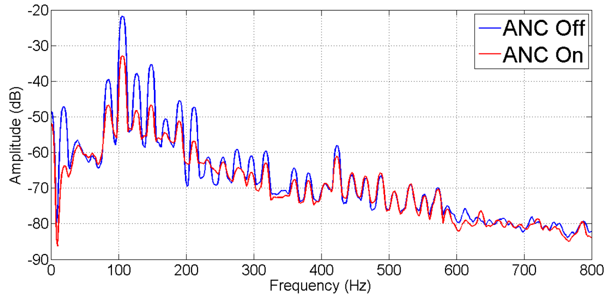
Performance Comparison of the TITO and CICO ANC Systems

Performance		ANC System	
		TITO	CICO
Noise reduction (dB)	Right ear	11-12	15
	Left ear	13-14	11-12
Computation	Multiplication	3290	549
	Addition	3278	546

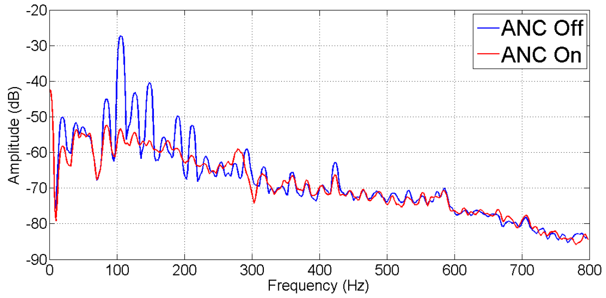
B. Reduction for Practical Noise

The performance of the CICO ANC headrest system was tested to reduce an example of motorcycle noise which consists of several harmonics. The recorded motorcycle noise is played by the primary loudspeaker. The length of control filter was set to 400.

The head manikin (Fig. 6) was replaced by KEMAR head simulator to measure the noise reduction at the KEMAR's ear location. Fig. 8(a) shows the noise reduction achieved at the manikin's right ear location. The result shows that the CICO ANC headrest system can reduce 5-10 dB of motorcycle noise at every major harmonics at the manikin's right ear even though the error microphone is placed at the headrest.



(a)



(b)

Fig. 8 Motorcycle noise reduction at KEMAR's ear location. (a) the error microphone at headrest, (b) KEMAR's ear microphones as error microphones.

Theoretically, the best noise reduction can be achieved at the error microphones locations. Therefore, the CICO ANC headrest system was tested by using KEMAR's ear microphones as the error microphones. Fig. 8(b) shows the noise reduction is better than the reduction shown in Fig. 8(a).

In order to achieve the optimized noise reduction while keeping the error microphones at the headrest, a technique called virtual sensing [12, 13] may be applied, which allows the ANC system to obtain the estimated residual noise at the ear location, but the physical microphone is located at the headrest location.

V. CONCLUSIONS

This paper demonstrated that simplification can be made without losing quiet zone performance in ANC headrest system. The CICO ANC headrest system achieved better performance than the TITO ANC headrest system based on the factors of noise reduction and system cost. Moreover, the CICO ANC headrest system achieved large enough quiet zone to cover head movement. Besides, the CICO ANC system can effectively reduce motorcycle noise at the ear location in real-time experiment.

In the future, more in-depth analysis of the CICO ANC headrest system, as well as the effect of combining two secondary loudspeakers and microphones will be analyzed. In addition, the use parametric array loudspeakers to form two quiet zones [14, 15] can be examined in this applications.

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