Evaluation of Speech Intelligibility for Feedback Adaptive Active Noise Cancellation Headset

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***Abstract*—In the noise environment of the modern society, everybody may be influenced by noise. Therefore, there have lots of workers must wearing the hearing protector to avoid the injury to its sense of hearing of various kinds of industrial noises in its environment. The conventional passive methods, such as ear muffs, are ineffective against low-frequency noise. To solve this problem, the present study developed a headset equipped with a digital signal processing system to implement feedback adaptive active noise cancellation (FbAANC) to reduce the low-frequency noise. The proposed FbAANC headset was effective against wideband industrial noise, with a maximal noise spectrum power reduction of 37.9 dB. The study also evaluates the effects of FbAANC headset on speech intelligibility on a disyllabic Mandarin word discrimination test (WDT) platform. Finally, the SNR below -10dB, the mean WDT score with FbAANC headset was superior to without FbAANC headset 13 to 32% through 30 subjects of normal hearing threshold for evaluation. These results suggest that the FbAANC headset would be useful for hearing protection in workplaces with high levels industrial noise.**

***Keywords*—Active noise cancellation, DSP, headset, industrial noise, WDT, speech intelligibility**

I. INTRODUCTION

Exposure to high levels of noise for long periods is known to cause the physical, physiological and psychological effects on human specially. Because of the upward spread of the masking effect, speech intelligibility is usually greatly affected especially by the low-frequency noise. The hearing loss of hearing aid wearer may also exacerbate due to the high ambient noise being amplified to an even higher level [1]. Therefore, the hearing protection is generally regarded as necessary to protect workers when they are exposed to noise at above 85 dBA sustained more than 8 hours.

The past passive noise cancellation are ineffective against low-frequency noise where the wavelength is large compared to the dimensions of the ear muffs. Because of the upward spread of the masking effect [2], speech hearing quality is usually greatly affected by many factors, especially by low-frequency noise.

This is the motivation for the development of a headset that provides excellent noise attenuation over the entire audio band by means of active noise reduction (ANR). The study would develop a headset to overcome the dilemmas for industrial workers under high level industrial noise, especially that of low frequencies noises. The headset is equipped with a DSP system to implement feedback adaptive active noise cancellation (FbAANC) using FxLMS algorithm to adapt to various industrial noise. Four typical industrial noises were used to evaluate the efficiency of the headset. Combined with the intrinsic ability of the headset to passively reduce high-frequency noise, the proposed headset was found to be effective against many wideband industrial noises.

Furthermore, an FbAANC headset may also attenuate speech and other significant sound, it may interfere with speech communication and with the perception of warning signals in industrial workplaces. We then designed an experiment of speech discrimination to estimate how the speech attenuation of the FbAANC headset influences speech perception in noise. We evaluate and clarify the hearing quality on a disyllabic Mandarin word discrimination test (WDT) platform [3]. The results imply that an FbAANC headset is valuable for hearing protection in workplaces with industrial noise, and it even also improve speech communication under high level industrial noise.

II. MATERIAL AND METHODS

2.1 THE FbAANC STRUCTURE AND ALGORITHM

The adaptive single channel feedback ANC system was first proposed by Eriksson [4]. The complete feedback adaptive ANC (FbAANC) system using the filtered-x least-mean-square (FxLMS) algorithm is illustrated in Figure 1, where is also required to compensate for the secondary path. From Figure 1, the reference signal is derived as an estimate of the noise d(n), which is expressed as

$$\hat{d}(n) = e(n) + \sum_{m=0}^{M-1} \hat{s}_m y(n-m) \qquad (1)$$

where $\hat{s}(m)$, m=0,1,…,M–1, are the estimated coefficients of equivalent filter $\hat{S}(z)$ that is an FIR filter of order M. The estimated antinoise $y(n)$ is generated as

$$y(n) = \sum_{l=0}^{L-1} w_l(n)\hat{d}(n-l) \qquad (2)$$

where $w_l(n)$, l=0,1,…,L–1, are the coefficients of the active-noise-cancellation filter $W(z)$ at time n, and L is the order of FIR filter $W(z)$. The filter's coefficients are updated by the FxLMS algorithm as follows:

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$$w_l(n+1) = w_l(n) + \mu \hat{d}'(n-l)e(n), \qquad l = 0,1,...,L-1 \tag{3}$$

Where μ is the step size, and

$$\hat{d}'(n) \equiv \sum_{m=0}^{M-1} \hat{s}_m d(n-m) \tag{4}$$

is the filtered reference signal processed by equivalent $\hat{S}(z)$.

The convergence rate and stability of the adaptive FxLMS algorithm is most influenced by the step size. In practical applications, we typically use the bounds

$$\frac{0.01}{LP_{\hat{d}(n)}} < \mu < \frac{0.1}{LP_{\hat{d}(n)}} \tag{5}$$

where $P_{\hat{d}(n)} = E\left[\hat{d}^2(n)\right]$ (6)

denotes the power of $\hat{d}(n)$, and $E[\cdot]$ denotes expected values [5].

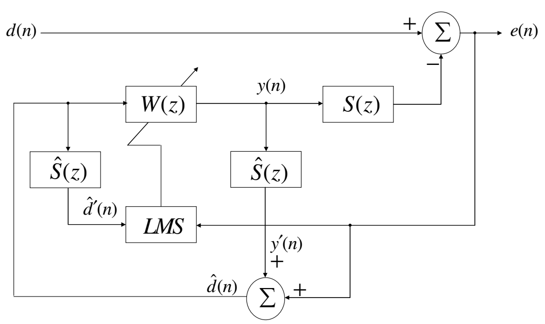


Figure 1. F_bAANC system using the FxLMS algorithm.

2.2 THE DESIGN OF FbAANC HEADSET

The headset with F_bAANC technique developed in this study is illustrated in Fig. 2 [6]. The F_bAANC was achieved by a core algorithm which was well known as the FxLMS algorithm. The FxLMS algorithm was implemented on a DSP starter-kit (DSK) board. The DSK board was equipped with a TI TMS 320c6711 floating-point processor and a 16-bit AD535 codec for signal input and output. This codec uses sigma-delta technology that provides analog-to-digital (A/D) and digital-to-analog (D/A) conversion at a fixed sampling rate of 8000 Hz.

The F_bAANC headset estimates a signal as the approximation of acoustic noise *d(n)* incident in free space. Signal $\hat{d}(n)$ is used as a reference signal to adapt the adaptive filter, *W(z)*, that generates an estimated antinoise signal *y(n)* to drive a noise-canceling loudspeaker so as to produce a sound signal with equal amplitude to noise *d(n)* and of opposite phase that will result a quiet zone within the confines of the headset.

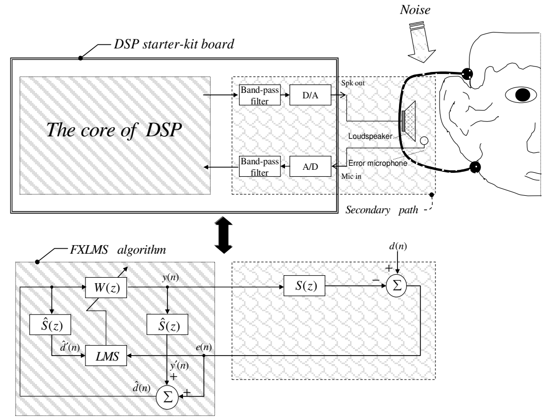


Figure 2. Block diagram of the FbAANC headset.

2.3 APPARATUS

To evaluate the degree of noise cancellation, the proposed FbAANC headset was tested using the setup shown in Fig. 3 that was housed within a standard audiometric chamber (Acoustic Systems, rs252). Three speakers produced test speech and industrial noises. The speech signals were presented through a loudspeaker located in front of the FbAANC headset at zero degrees azimuth, and the industrial noises were presented through two loudspeakers positioned in front of the FbAANC headset at 45 degrees azimuth to the right and left. All three speakers were located 1 meter from the headset [7]-[8].

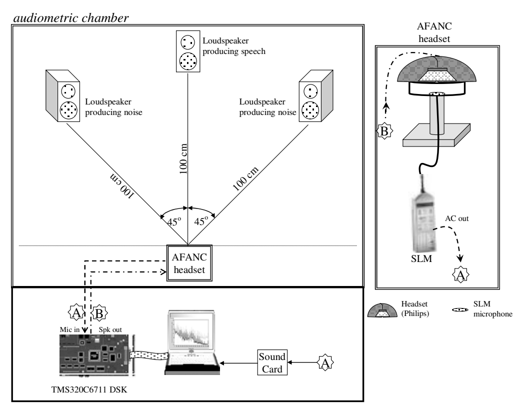


Figure 3. Schematic diagram of the test equipment. SLM, sound level meter

2.4 THE DISYLLABIC MANDARIN WORD DISCRIMINATION TEST

2.4.1 MATERIAL SELECTION AND CONDITIONS

◆ DISYLLABIC WORD LISTS

In the past research of mention above, the subjective tests are designed for English speaking population. However, there are more than 90% of people do not speak English and need to design a standardized speech test for each language. Mandarin is different from English in aspect of tones which are associated with different meanings.

Chiang (2005) proposed the genetic algorithm to search Mandarin disyllabic words that accord with the phonemic balance of a lexical corpus. The genetic algorithm is a well-known method with the search property of effectiveness, robustness and low complexity. Finally, the methods find 300 disyllabic Mandarin word materials with 6 word lists and each have 50 words. Therefore, our research would continue using these word lists as the experimental materials for word discrimination test.

◆ SPEECH MATERIALS CONTAMINATED BY TRANSFORMER NOISE

To verify the influence of the FbAANC headset system on speech intelligibility with noise, we prepared two set of noisy speech for the WDT. The recorded speech was played whilst contaminated by transformer noise with different levels to obtain the noisy speech with signal-to-noise ratios (SNRs) of 0, –5, –10, -15, -20 and –25 dB.

The noisy speech was formed by mixing the recorded speech of 25 dB hearing level (dBHL) with the transformer noise of 25, 30, 35, 40, 45, and 50 dBHL, respectively. The noisy speech sets with and without noise cancellation were prepared as the following procedure. The transformer noise was presented through two loudspeakers positioned in front of the FbAANC headset system with 45 degrees azimuth at right and the left sides. The recorded speech was presented through the loudspeaker located in front of the FbAANC headset system at zero degrees azimuth. For the noisy speech without noise cancellation, the transformer noise was played first for a period, and the recorded speech was then played. The mixing sound was recorded with the FbAANC headset system turning-off. For the noisy speech with noise cancellation, the procedure was similar only except with the FbAANC headset system turning-on. The noisy speech was recorded as different files via the sound card of the computer with a sample rate of 22 kHz.

2.4.2 CLASSIFICATION OF WORD LISTS

There are six word lists with fifty disyllabic words, and the total available words were 300. The recorded speech of each word was contaminated by transformer noise with six different S/N ratios. Therefore, there are then 1800 noisy speech without noise cancellation and 1800 noisy speech with noise cancellation.

Thirty subjects, 15 men and 15 women with age of 19-30 years old, attended the WDT to evaluate the effectiveness of the FbAANC headset system. All of them were fluent in Chinese and had normal hearing thresholds of less 25dB HL from 125Hz to 8 kHz. The subjects were divided into six groups (Group0~5), and each subject in a group attended the WDT with same combination of the noisy speech. Each group was tested by the noisy speech arranged as TABLE I. With the arrangement in the table, the subjects of group two, for example, were test by the noisy speech of word list 1 with SNR of -20dB, word list 2 with SNR of -25dB, word list 3 with SNR of 0dB, word list 4 with SNR of -5dB, word list 5 with SNR of -10dB, and word list 6 with SNR of -15 dB. The other groups had similar arrangements with the word lists associating with different SNR ratios.

TABLE I. The assign of noisy speech for each group attended the WDT. 2_-20 means the noisy speech of word list 2 with SNR of -20dB without noise cancellation; 2h_-20 , means the noisy speech similar to 2_-20 but with noise cancellation.

Group 0		Group 1		Group 2		Group 3		Group 4		Group 5	
List_ snr(dB)	Listh_ snr(dB)	List_ snr(dB)	Listh_ snr(dB)	List_ snr(dB)	Listh_ snr(dB)	List_ snr(dB)	Listh_ snr(dB)	List_ snr(dB)	Listh_ snr(dB)	List_ snr(dB)	Listh_ snr(dB)
1_0	1h_0	1_-5	1h_-5	1_-20	1h_-20	1_-25	1h_-25	1_-10	1h_-10	1_-15	1h_-15
2_-5	2h_-5	2_0	2h_0	2_-25	2h_-25	2_-20	2h_-20	2_-15	2h_-15	2_-10	2h_-10
3_-10	3h_-10	3_-15	3h_-15	3_0	3h_0	3_-5	3h_-5	3_20	3h_20	3_25	3h_25
4_-15	4h_-15	4_-10	4h_-10	4_-5	4h_-5	4_0	4h_0	4_-25	4h_-25	4_-20	4h_-20
5_-20	5h_-20	5_-25	5h_-25	5_-10	5h_-10	5_-15	5h_-15	5_0	5h_0	5_-5	5h_-5
6_-25	6h_-25	6_-20	6h_-20	6_-15	6h_-15	6_-10	6h_-10	6_-5	6h_-5	6_0	6h_0

2.4.3 EXPERIMENTAL FACILITIES AND TESTING PROCEDURE

The operation interface for the WDT was designed by the LabVIEW 7.1 (National Instruments) graphical language. To control and to output the sound pressure accurately, we chose the DAQ device PXI-4461 (National Instruments) for standard headset TDH-50. The subjects seat on the inner shell of audiometric chamber for the WDT, and the other facilities are housed outside the audiometric chamber as shown in Figure 4 to avoid the interference from the instruments.

Every subject must pass the audiometric test by a standard instrument AC-40. The Figure 5 shows the response screen for the WDT. During the WDT, a leading sentence “Please choice the answer you hear” was presented and the noisy speech (target speech) was then followed one second later. There are four disyllabic Mandarin words on the response screen; one is the target speech, and the others are confusion words. The four items were random arrange on the response screen in every question. Each subject of each group must response to 600 questions, and each test needed about 1 hour.

Figure 4. The systematic apparatus for the WDT.

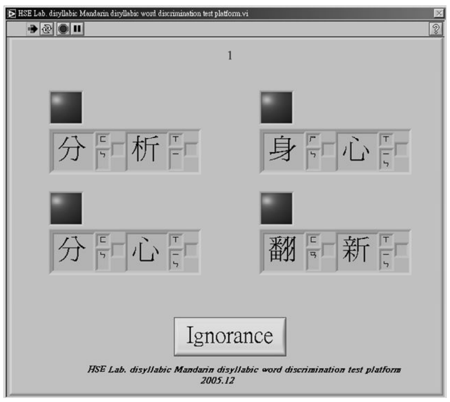


Figure 5. The response screen for the WDT of disyllabic Mandarin word. The disyllabic Mandarin word and its Hanyu Pinyin of 分心, 身心, 分析, 翻新 are "fen1 xyin1", "shen1 xyin1", "fen1 xyi1", "fan1 xyin1".

III. EXPERIMENTAL RESULTS

3.1 PERFORMANCE OF FbAANC HEADSET

The result shown in Fig. 6, the passive noise cancellation (PNC) show the DSP system when run off, hence the error microphone capture the noise signals through the insulation by headset materials and the pure tone noise reduce 4 to 16 dB above 1250Hz. That is conventional close-type headset without ANC technique give good attenuation of noise in the upper frequency range. When the DSP system run on, it would achieve roughly attenuation 40dB to 60dB in the 63Hz to 1250Hz frequency range with ANC technique.

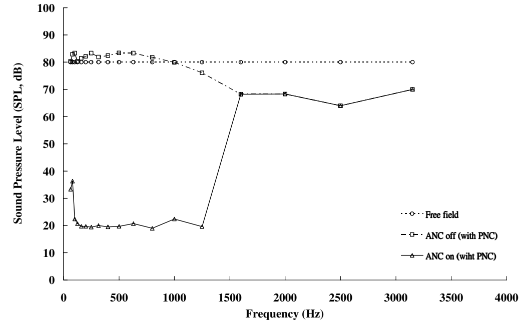
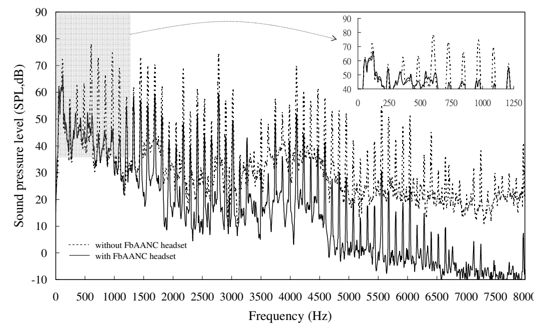
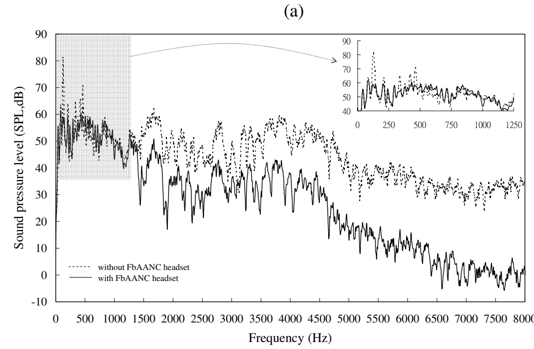


Figure 6. Comparison of the intensity versus frequency of pure tone with three activity conditions evaluated for FbAANC headset. The 'Free field', 'ANC off (with PNC)' and 'ANC on (with PNC)' were indicate that without headset and DSP system run off, with headset but DSP system run off, and with headset and DSP system run on, respectively.



(a)



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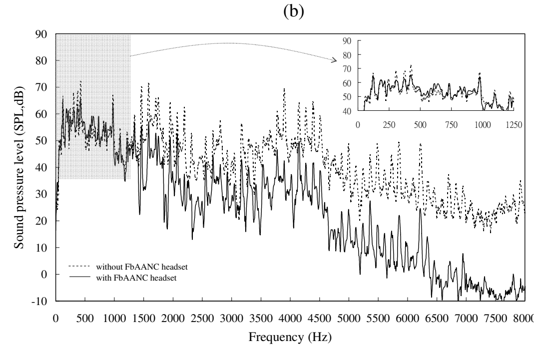

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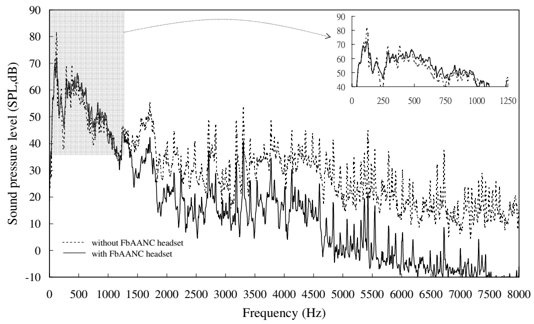

(d)

Figure 7. Reduction in the spectrum power for four industrial noises: (a) transformer, (b) fan, (c) power station, and (d) compressor.

Four types of industrial noise were mainly used to evaluate the noise-cancellation performance of the proposed FbAANC headset. The transformer noise had dominant components at harmonically related frequencies that could be reduced by up to 37.9 dB, as shown in Fig. 7(a). The other industrial noises exhibited wider power spectra around 250 and 1200 Hz, and did not have obvious harmonically related components. However, their individual dominant components were still significantly cancelled, by 23.8, 8.2, and 9.5 dB, and all their spectral power was reduced to below 80 dB SPL, as shown in Fig. 7(b)–(d).

3.2 THE RESULTS OF WDT EVALUATION

The WDT evaluation of with and without FbAANC headset was shown in Fig. 8. The mean WDT score is the average of list 1 to 6 on the same SNR. When the SNR above the -10dB, the mean WDT score were both above 80%. But, the score with FbAANC headset was less than without FbAANC headset 6 to 8% on the SNR of -5 and 0 dB. However, the SNR below -10dB, the score with FbAANC headset was great than without FbAANC headset 13 to 32%.

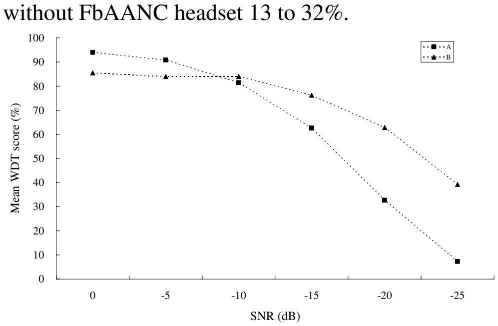

Figure 8. The mean scores by averaging all lists. The 'A' and 'B' declare that without and with the noise cancellation respectively.

IV. Discussions

4.1 ABOUT THE PERFORMENCE OF THE FbAANC HEADSET SYSTEM

The proposed FbAANC headset system also exhibits the interesting noise-reduction characteristics for the industrial noises. It shows that there is remarkable noise reduction above the frequency of 1200 Hz irrespective of the type of noise presented. This should be attributable to the intrinsic passive noise reduction of the full-size closed headset. The FbAANC headset system shows its active noise cancellation most effective between 250 and 1200 Hz. The dominant frequency components within this frequency range can almost be reduced to an acceptable level for the four industrial noise used by the study.

Real industrial noises always contain wideband harmonic components with nearly periodic frequency that usually depends on type of machinery. A feedback configuration based on linear error-prediction techniques [9] was proposed to provide limited noise attenuation over a restricted frequency range for periodic or band-limited noise. Previous simulations have suggested that an integrated feedback active noise control system can reduce engine noise by more than 30 dB [10]. In the present study, we have been demonstrated experimentally that dominant components of a wide band noise could be cancel with the maximal spectrum power reduction more than 37.9dB. Of the four types of industrial noises tested, the proposed FbAANC headset system showed its best cancellation for the transformer noise. This is attributable to transformer noise having dominant near-periodic components.

4.2 ABOUT THE WDT EVALUATION OF NOISY SPEECH

About the WDT evaluation of noisy speech with the proposed FbAANC headset system, the WDT scores with noise cancellation is not better than those without noise cancellation when the noisy speech with the SNR of 0 and -5dB. This result seems to been a exception beyond our expectation. It is interesting to explore the reasonable explanation for such a phenomenon.

In order to find out these questions, figure 9 show the waveforms and the spectra of the disyllabic Mandarin speech "(xi1 xi4)" under different conditions. The figure gives us some implication to explain the exception of the WDT scores stated above. The waveforms and the spectra in figure shows that the target speech "(xi1)" has its obvious consonant and vowel waveforms in original speech and the noisy speech without noise cancellation. After processed by the noise cancellation of the F_bAANC headset system, consonant waveforms of the noisy speech would be heavily reduced by PNC and ANC effects. The consonant of speech "(xi1)" composed of high frequency is especially attenuated by the PNC techniques (upper 1.5k Hz) compare in the third spectral graph on figure 9. Such massive reduction of high frequency information causes the subjects more confusing and leads them to give an answer of "ignorance". That is according to the analyzed result of wrong answers of the WDT evaluation.

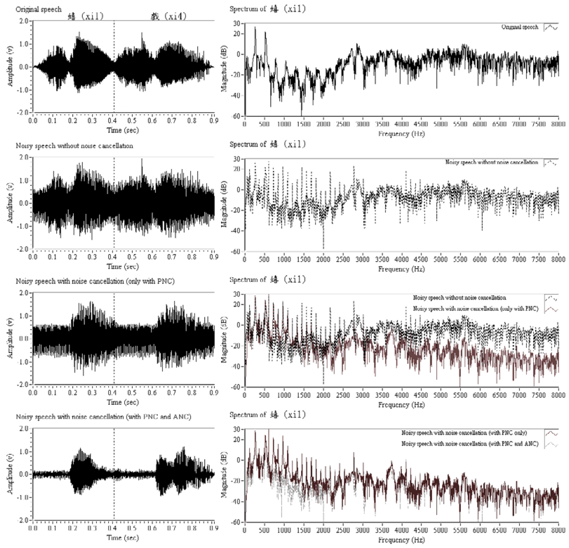

Figure 9. The waveform and spectra of the disyllabic Mandarin speech "(xi1 xi4)" under different conditions. The top plot is the original speech, the second plot is the noisy speech without noise cancellation, the third plot is the noisy speech with passive noise cancellation only and the lowest plot is the noisy speech with passive and active noise cancellation.

V. Conclusions

The study proposed an FbAANC headset system that can work as a hearing protector against wideband industrial noises. It particularly has the potential and is useful for the workers who may work in the workplaces with great industrial noise. To optimally cancel unwanted acoustic noise, the FbAANC headset system adopted an adaptive controller with FxLMS adaptive algorithm; that was implemented on a TI TMS320C6711 DSP board. The performance evaluation shows that the FbAANC headset system can effectively treat different wideband industrial noises with a maximal power reduction of dominant noise spectrum by 37.9 dB. The WDT results are also shown that it can improve the speech intelligibility by 13 to 32% when noisy speech with SNR less than -10dB. These results imply that the proposed FbAANC headset system has the potential to work as a hearing protector for the workers in the workplaces with great industrial noise. It would be especially valuable for the hearing-impaired person who wear hearing aids and face to different industrial noises in their workplaces.

Acknowledgment

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