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Using A-weighting for Psychoacoustic Active Noise Control

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Abstract— **Conventional adaptive active noise control (ANC) methods aim to attenuate the acoustic noise over the frequency band of interest indiscriminately using the sound pressure level (SPL) measurement (or the measurement of the residual error variance). However, SPL does not correctly reflect the human perception of attenuated noise due to the frequency selective sensitivity of human hearing system. A-weighting is a commonly used weighting filter for measuring the noise. This weighting filter quantifies frequency response of the human ears and hearing system. In this paper, we aim to improve the performance of adaptive noise cancellation method from the psychoacoustic point of view by incorporating the A-weighting into the ANC system design. Loudness is used as the psychoacoustic criterion for evaluating the ANC system performance. Simulation results illustrate the effectiveness of the proposed method.**

I. Introduction

Active noise control (ANC) technique [1] works on the principle of destructive interference between a primary and secondary noise source. An "anti-noise" signal with equal amplitude and opposite phase of the noise is generated via a loudspeaker to cancel out the primary noise sound acoustically at the target zone.

Although a variety of adaptive ANC algorithms have been developed [2][3], we should notice that the ultimate goal of reducing the acoustic noise is to minimize its effects on human hearing system. In other words, what is important is that how human being perceives, and feels comfortable when hearing the attenuated acoustic noise. Almost in all conventional ANC systems, the adaptive filtering algorithms aim to reduce the noise by minimizing the variance of the error between the primary noise and the anti-noise signals, i.e. using the mean square error (MSE) criterion. Thus, only the average power of the error is minimized by ignoring distribution of the error as a function of frequency. The use of minimum MSE (MMSE) criterion alone may not be an appropriate measure for the effectiveness of noise reduction on human hearing. In a similar way, SPL measure alone may not represent the quality of the reduced sound when human hearing is concerned. That is, as indicated in later section, a residual noise with higher SPL may sounds quieter for a human being. By research on psychoacoustic characteristics [4], it is found empirically that human hearing sensation has selective sensitivity to different frequencies. For example, our hearing system may not feel equally loud for two tones with same amplitude but different frequencies. This psychoacoustic fact brings up the need to improve the current ANC system by taking into account the special human hearing property.

In order to attenuate the noise considering the human hearing, we need to modify the conventional ANC structure to include the component which can reflect psychoacoustic characteristics. Gan proposed an ANC system with equal-loudness compensation [5] based on adaptive active noise equalizer [6]. The equal loudness property was utilized to adjust the coefficient which was used to control the gain of equalizer. But this approach was applied only to a narrow-band noise signal. A broadband active noise equalizer was developed with noise shaping capability [7]. Performance of the noise shaping method is quite sensitive to the amplitude of the shaping filter $C(z)$. The shaping of the residual noise may even be achieved at the cost of degrading the ANC system performance. Another filtered-E least-mean-square (FELMS) method was proposed to shape the spectrum of the residual noise with lower complexity and better performance [8]. Based on the structure of FELMS, we will incorporate the noise weighting into ANC in order to improve the noise attenuation for psychoacoustic purposes.

In this paper, A-weighting [9] is chosen as the psychoacoustic component in ANC system. It quantified human hearing's sensitivities to different frequencies. Based on the A-weighting curve, human hearing sensitivity peaks at 3 kHz approximately.

With regard to the psychoacoustic evaluation, we utilize loudness, one of the psychoacoustic metrics, for measuring the performance of the ANC system. Loudness belongs to the category of intensity sensations and has been shown to correlate acceptably well with the subjective testing results. It corresponds most closely to the sound intensity of the stimulus. Loudness comparisons can lead to more precise results than SPL, which is typically used in acoustic/audio noise measurements. Loudness can be calculated quantitatively by the ISO 532B [10] norm in unit of *sone* [4]. Corresponding program was also developed in [11].

The rest of the paper is organized as follows. In Section 2, conventional ANC system and the concept of loudness is described. The proposed ANC system with A-weighting is introduced in Section 3. Section 4 provides the simulation results using multi-tone signal with and without white noise signals, and realistic noise signals- factory background noise.

II. Problem Statement

The flowchart of a conventional ANC system with filtered-X LMS (FXLMS) structure is shown in Fig. 1. P(Z) represents

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system response of the primary path (the acoustic cavity) with a reference sensor measuring the input signal (the source noise signal) and an error sensor measuring the output signal or the attenuated signal at the point where noise cancellation occurs. Secondary path S(Z) presents system response for all the electrical and acoustical signal transmission paths from the cancelling speaker to the cancelling point. $\hat{s}(Z)$ is the estimated version of S(Z). Adaptive filer W(Z) is adjusted to minimize the residual noise e(n).

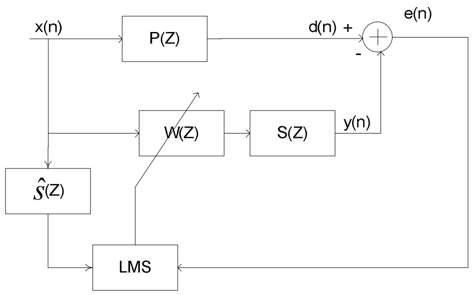

Fig. 1 Conventional ANC system

To evaluate the noise attenuation performance, SPL is adopted to fulfill this task. However, it has been determined that human ear does not respond equally to full frequency band. Therefore the conventional ANC system should be modified incorporating the human hearing characteristic. Also, a psychoacoustic criterion is necessary for performance evaluation. For that reason, loudness representing the sound intensity in human's ear is utilized in this paper. To define loudness, the level of 40 dB of a 1 kHz tone is proposed to give the reference for loudness, i.e., 1 *sone*.

Loudness can be calculated quantitatively with the following function:

$$L = \int_0^{24\,Bark} N' dz \quad (1)$$

where L is the loudness, N' is the "specific loudness", i.e., the loudness in a specific critical band, which is measured in units of sone/bark. Bark is the unit which defines the scale corresponding the first 24 critical bands of hearing. Thus, the overall loudness is the integral of specific loudness over all critical-band rates.

In order to get the specific loudness, we use the following equation:

$$N' = 0.08\left(\frac{E_{TQ}}{E_0}\right)^{0.23}\left[\left(0.5+0.5\frac{E}{E_{TQ}}\right)^{0.23}-1\right]\frac{sone_G}{Bark} \quad (2)$$

where, E_{TQ} is the excitation at threshold in quiet and E_0 is the excitation that corresponds to the reference intensity $I_0 = 10^{-12} W/m^2$. The subscript G at the unit "sone" is to indicate that the loudness here is produced using the critical-band levels.

III. Psychoacoustic ANC with A-weighting

A. *A-Weighting:*

Research of A-weighting began with the work on Equal-loudness contour by Fletcher and Munson in 1933. The weighting matches human hearing response approximately.

A-weighting is calculated by (3) and (4)

$$R_a(f) = \frac{12200^2 \cdot f^4}{(f^2+20.6^2)(f^2+12200^2)(f^2+107.7^2)^{0.5}(f^2+737.9^2)^{0.5}} \quad (3)$$

$$A = 2.0 + 20\log(R_a(f)) \quad (4)$$

The frequency response is shown in Fig. 2. Note that human ear is more sensitive to frequencies between 1 kHz and 5 kHz than other higher or lower frequencies.

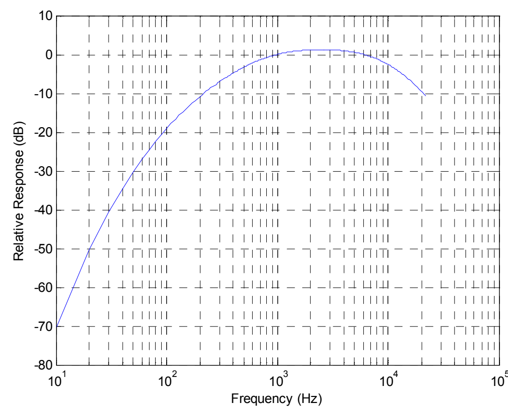

Fig. 2 Frequency response of A-weighting filter

B. *Proposed ANC system with A-weighting:*

In order to incorporate the noise weighting in ANC, we use FELMS structure [8], the modified ANC system shown in Fig. 3. $H_{nw}(z)$ represents the noise weighting filter. We utilize A-weighting in this paper. As shown in Fig. 3, the residual noise $e(n)$ is filtered by noise weighting filter $H_{nw}(z)$. The result of the LMS adaptive filter is to minimize $e_h(n)$, the output of noise weighting filter.

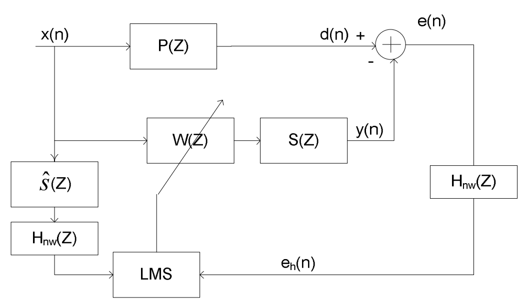

Fig. 3 ANC system with noise weighting

The coefficient of the adaptive filter can be expressed as:

$$\mathbf{w}(n+1) = \mathbf{w}(n) + 2\mu e_h(n)[x(n) * \hat{s}(n) * h_{nw}(n)] \quad (5)$$

Note that

$$e_h(n) = e(n) * h_{nw}(n), \quad (6)$$

we can further obtain the coefficient updating equation:

$$\mathbf{w}(n+1) = \mathbf{w}(n) + 2\mu e_h(n)[x(n) * \hat{s}(n) * h_{nw}(n)] \quad (7)$$

where, $\mathbf{w}(n)$ is the coefficients of adaptive filter, μ is the step size of adaptive filter, $e_h(n)$ is the output of noise weighting filter, $\hat{s}(n)$ is the estimated version of secondary path impulse response, $h_{nw}(n)$ is the impulse response of noise weighting filter.

Furthermore, the structure in Fig. 3 can be simplified as an equivalence to Fig. 4 by combining $H_{nw}(z)$ to the input node. It is easy to see that the input signal is filtered by the noise weighting filter.

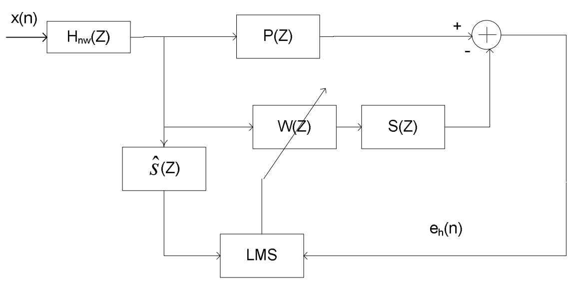

Fig. 4 Simplified ANC system with noise weighting

IV. SIMULATIONS

We present several simulation results illustrating the effectiveness of the new ANC system. Primary transfer function $P(z)$ and secondary transfer function $S(z)$ are chosen with frequency response shown in Fig. 5 and Fig. 6. The filter length of $W(z)$ is 200 and the step size is 0.1. The sampling frequency is 44.1 kHz.

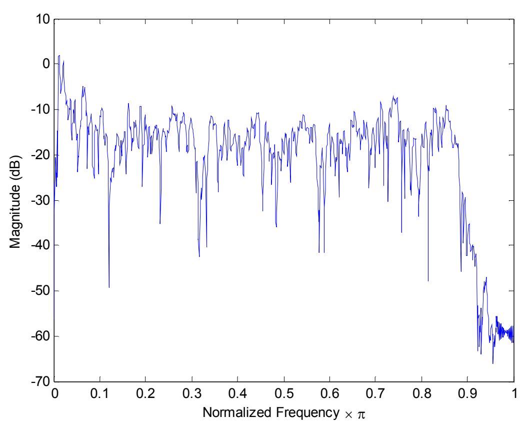

Fig. 5 Frequency response of the primary path used in the simulation

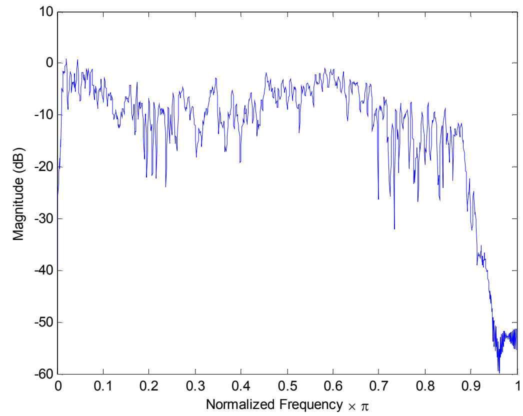

Fig. 6 Frequency response of the secondary path used in the simulation

A. Multi-tone noise signal:

The first simulation uses multi-tone signal as input with the following frequency components: 0.2, 0.3, 1, 2, 3, 10, 20 kHz. The reason to choose this simple synthetic noise signal is to make more obvious the differences between the results of two ANC systems. Furthermore, these specific frequencies represent the human hearing frequency range with different sensitivity.

Simulation results are shown in Table 1. $e_1(n)$ is the residual noise of the proposed ANC system incorporating the A-weighting. $e_2(n)$ is the residual noise of the conventional ANC system. The comparison is made in terms of two types of criteria: sound pressure level (SPL) and loudness.

Table 1. Comparison of proposed ANC system and conventional ANC system in terms of SPL and loudness

	SPL(dB) Beginning	SPL (dB) End	Loudness(sone) Beginning	Loudness(sone) End
$e_1(n)$	91.5171	74.0865	34.0300	1.2710
$e_2(n)$	91.5171	73.7746	34.0300	1.9480

In Table 1, we record the value of SPL and loudness in the beginning period and after system convergence. By comparing the results for $e_1(n)$ and $e_2(n)$, it is interesting to notice that SPL increases by 0.31 dB after we introduce the noise weighting into the ANC system, which means the residual noise should be louder in new ANC system from conventional point of view. But the loudness is reduced from 1.9480 *sone* to 1.2710 *sone*, which is 34.75% off. This result demonstrates that SPL value is not necessarily proportional to the loudness, which should quantitatively measure the human hearing sensation. More importantly, it proves that the noise weighting improves the ANC system's noise attenuation with respect to the psychoacoustic criterion.

B. Mixture of Multi-tone noise and white noise:

To access the influence of white noise, we combine the above multi-tone signal with additive Gaussian white noise at SNR = 10 dB. The results in Table 2 show achieving 10.45% improvement in loudness.

Table 2. Comparison of proposed ANC system and conventional ANC system in terms of SPL and loudness

	SPL(dB) Beginning	SPL (dB) End	Loudness(sone) Beginning	Loudness(sone) End
$e_1(n)$	89.8202	75.5871	36.2300	10.4080
$e_2(n)$	89.8202	74.9695	36.2300	11.9540

C. Realistic Noise:

The above simulations are all conducted using synthetic noise signals. In order to evaluate the practical effect of the incorporation of noise weighting, we also adopt real-world noise signals for simulations. We test the new system using factory background noise with length of 5 seconds. Power spectrum is shown in Fig. 7.

Table 3. Comparison of proposed ANC system and conventional ANC system in terms of SPL and loudness for factory background noise

	SPL(dB) Beginning	SPL (dB) End	Loudness(sone) Beginning	Loudness(sone) End
$e_1(n)$	58.9349	45.8672	4.3110	1.2110
$e_2(n)$	58.9349	45.8695	4.3110	1.2530

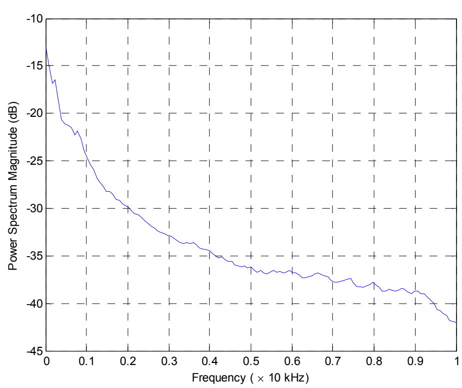

Fig. 7 Power spectrum of factory background noise signal

From the result shown in Table 3, it is seen that the SPL is almost the same for the two cases. However, the loudness is reduced by 3.35%.

V. CONCLUSION

ANC has attracted a considerable amount of research attention because noise control becomes quite important due to rapid industry development. It is well known that human ear has special responding characteristics for different frequency components of noise signal. However, conventional ANC system does not consider perceptual effects of human hearing system. In this paper, we incorporated a psychoacoustic component into the ANC system design to improve noise attenuation in terms of human perceptual sensation. A-weighting approximately quantified the relationship of human ear response to frequency. A-weighting was utilized in the new ANC system based on FELMS structure. Moreover, loudness was used in this paper as the psychoacoustic criterion for performance evaluation.

Simulations were conducted for different signals: multi-tone signal without and with additive white noise, realistic environmental noise signal. Comparisons were made between conventional and new ANC systems based on SPL and loudness criteria. Loudness was reduced in new ANC system by 34.75%, 10.45% and 3.35%, respectively. It was interesting to note that SPL performance was not improved and even degraded in some cases. That provided an explanation regarding the issue in a conventional ANC system that sometimes human ear might not perceive much difference although SPL performance was improved.

Future work will include subjective test to verify the effectiveness of the proposed method. Also, the residual noise shaping technic should be modified to improve the performance for realistic noise signals.

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