

Psychoacoustic Hybrid Active Noise Control System

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ABSTRACT

In conventional active noise control (ANC) system, the primary noise is attenuated over the frequency band of interest based simply on the error signal, which does not take into account the human perception of noise. Hence, researchers have developed psychoacoustic ANC system to improve its noise reduction performance from psychoacoustic point of view. However, in this psychoacoustic ANC system, there may be a disturbance that is uncorrelated with the primary noise at the error sensor, which can severely degrade the system's noise reduction performance. Hence, in this paper, a psychoacoustic hybrid ANC system is proposed, which can simultaneously control both the correlated primary noise and uncorrelated disturbance from psychoacoustic point of view. Loudness is used as the psychoacoustic criterion for evaluating the system's noise reduction performance. Simulation results show the effectiveness of the proposed psychoacoustic hybrid ANC system.

Index Terms— Active noise control, Loudness, Psychoacoustic active noise control, Hybrid active noise control, Psychoacoustic hybrid active noise control

1. INTRODUCTION

Active noise control (ANC) [1, 2] is a well-developed technique for reducing low-frequency acoustic noise (< 500 Hz), where traditional passive methods, such as enclosures and barriers, are bulky, costly and ineffective. ANC is based on the principle of superposition and aims to cancel out the undesired acoustic noise (or primary noise), by generating an “anti-noise” that has equal amplitude and opposite phase as the primary noise. Thus, when this anti-noise is combined with the primary noise, destructive interference between them results in noise cancellation around the error sensor.

Although many different types of adaptive algorithms, which are generally based on the error signal, have been developed to improve the performance of ANC system in literature, ultimately, ANC must still be designed based on how humans perceive noise. The conventional ANC system relies on the mean square error (MSE) as the criterion in the adaptive filtering algorithms, and thus, the noise is reduced by minimizing the variance of the error signal between the

primary noise and anti-noise. Since this scheme treats different frequency components of the noise identically, it does not match with our human auditory system, which performs frequency selective processing [3]. Hence, different frequency components of the noise should be processed differently in the ANC system to match the behavior of our human auditory system.

Psychoacoustic models [4] have been incorporated into ANC systems to better match the perceived noise level in the human auditory system. In [5], Gan proposed an ANC system with equal-loudness compensation for the adaptive active noise equalizer (ANE). In [6], the filtered-error least-mean-square (FELMS) algorithm was applied to the ANC system so that noise weighting can be incorporated. Based on the FELMS algorithm, researchers have developed psychoacoustic ANC system [7, 8, 9]. Also, loudness, which can be calculated according to [10], is used as the criterion to evaluate the noise reduction performance of the system.

However, all the above proposed psychoacoustic ANC systems are based on the feedforward structure. Hence, their performances will be severely degraded in the presence of an uncorrelated disturbance at the error sensor, which can happen in many real-world ANC applications. Being uncorrelated with the primary noise, this uncorrelated disturbance cannot be controlled by ANC of feedforward structure. Related examples can be found in [11] and [12].

Therefore, in order to improve the performance of the psychoacoustic ANC system in the presence of an uncorrelated disturbance appearing at the error sensor, hybrid ANC system [13] is utilized, which consists of both feedforward and feedback adaptations. Feedforward adaptive filter is used to control the correlated noise level, while feedback adaptive filter is used to cancel the uncorrelated disturbance based on an internally generated reference signal. Hence, in this paper, we propose a psychoacoustic hybrid ANC system that can reduce both correlated primary noise and uncorrelated disturbance, based on the loudness perception of human beings.

The rest of this paper is organized as follows. In Section 2, the conventional psychoacoustic ANC system is introduced and the associated problem is described. The proposed psychoacoustic hybrid ANC system is presented in Section 3. Simulation results are shown in Section 4 to verify the performance improvement of the proposed ANC system. Section 5 concludes this paper.

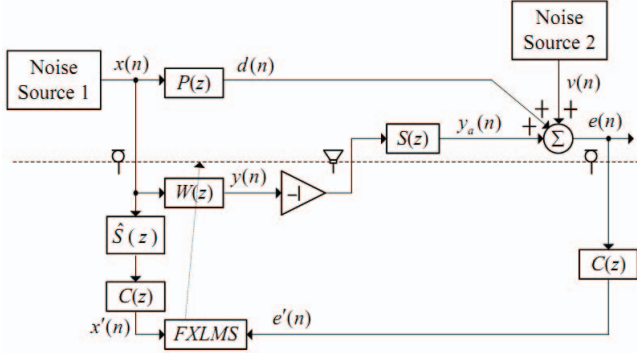


Figure 1: Block diagram of the conventional psychoacoustic ANC system

2. PSYCHOACOUSTIC ANC SYSTEM

Figure 1 shows the block diagram of the conventional psychoacoustic ANC system. In this system, $P(z)$ represents the transfer function of the primary path, which is the acoustic response from the reference sensor to the error sensor, and $S(z)$ represents the transfer function of the secondary path, which is from the secondary loudspeaker to the error sensor including all the electrical and acoustical signal transmission paths.

The primary noise $d(n)$ is obtained by transmitting the reference noise $x(n)$ from the noise source through the primary path $P(z)$. The anti-noise $y_a(n)$ is obtained by transmitting the output signal $y(n)$ of the adaptive filter $W(z)$ through the secondary path $S(z)$. $d(n)$ and $y_a(n)$ interfere with each other destructively, and the error signal $e(n)$ is captured by the error sensor and feed back to the controller to update the coefficients of the adaptive filter $W(z)$ as follows:

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \mu \mathbf{x}'(n) e'(n), \quad (1)$$

where μ is step size for the FXLMS algorithm, and

$$\mathbf{x}'(n) = \hat{\mathbf{s}}(n) * \mathbf{x}(n) \quad (2)$$

is the filtered reference noise. $\hat{\mathbf{s}}(n)$ is the impulse response of the secondary path estimate $\hat{S}(z)$. The filtered error signal $e'(n)$ is calculated as

$$e'(n) = e(n) * c(n), \quad (3)$$

where $e(n)$ is the error signal, which is also known as the residual noise, and $c(n)$ is the impulse response of the noise weighting filter $C(z)$.

In order to reflect the frequency response of the human auditory system, the noise weighting filter $C(z)$ needs to be carefully selected. However, the conventional psychoacoustic ANC system will suffer from severe performance degradation when an uncorrelated disturbance is present at the error sensor.

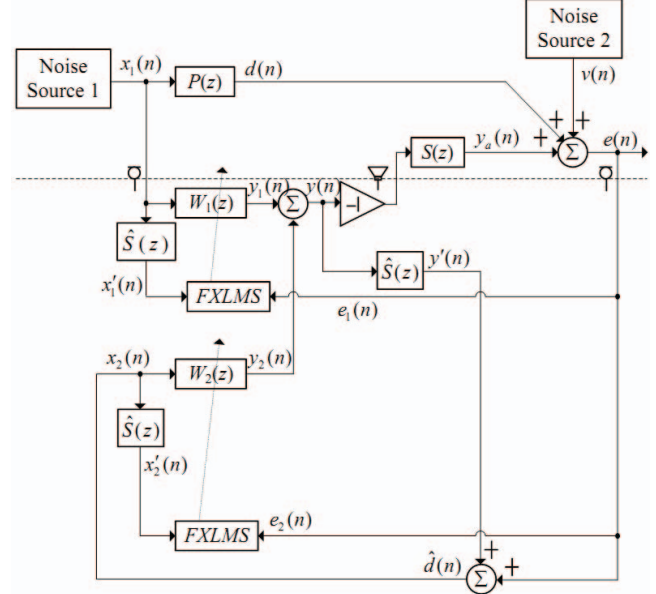


Figure 2: Block diagram of the conventional hybrid ANC system

3. PROPOSED PSYCHOACOUSTIC HYBRID ANC SYSTEM

To solve the problem of the conventional psychoacoustic ANC system mentioned above, hybrid ANC system can be utilized. The block diagram of the conventional hybrid ANC system is shown in Fig. 2 above. But in the conventional hybrid ANC system, noise is attenuated based on the sound pressure level at the error sensor and not based on the subjective loudness level. To better match the behavior of our human auditory system, loudness measures should be included in the conventional hybrid ANC system.

Hence, a combination of the FELMS algorithm used in the conventional psychoacoustic ANC system and the hybrid ANC system can be developed to take into account the loudness level of both primary noise and uncorrelated disturbance. The block diagram of the proposed psychoacoustic hybrid ANC system is shown in Fig. 3 below.

The proposed psychoacoustic hybrid ANC system is formed by inserting three identical A-weighting filters $C(z)$ [14] into the conventional hybrid ANC system.

These filters are inserted in the error signal path, and at the reference signal paths of feedforward and feedback sections. Basically, these A-weighting filters mimic human hearing response to give different weightings to different frequency components in the noise signal. In this paper, loudness representing the sound intensity in human's ear is selected as the psychoacoustic criterion to evaluate the system's noise reduction performance. To define loudness, the level of 40 dB of a 1 kHz tone is proposed to give the reference for loudness of 1 sone. The loudness can be quantitatively calculated by using the following equation:

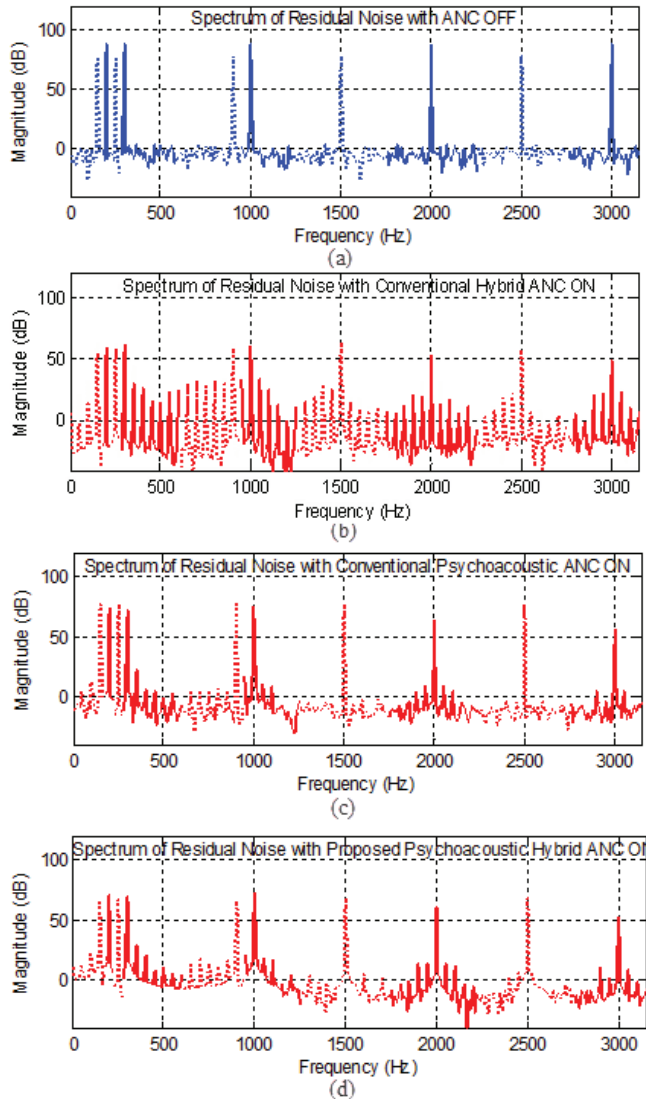


Figure 4: Residual noise (correlated primary noise(solid line) + uncorrelated disturbance(dotted line)) (a) when the ANC is OFF, (b) when the conventional hybrid ANC is ON, (c) when the conventional psychoacoustic ANC is ON and (d) when the proposed psychoacoustic hybrid ANC is ON

uncorrelated disturbance $v(n)$, but our proposed ANC system is able to. Hence, if the uncorrelated disturbance is significant compared to the primary noise, then our proposed ANC system should generate a residual noise that has smaller SPL value and is perceived softer compared to the conventional psychoacoustic ANC system. This can be easily verified by comparing the 4th row and 5th row in Table 1 above. Hence, our proposed ANC system is able to attenuate both the correlated primary noise $d(n)$ and the uncorrelated disturbance $v(n)$, as well as taking into account the frequency selectivity of the human auditory system.

5. CONCLUSIONS

Conventional hybrid ANC system does not consider the fact that our human auditory system has a non-uniform frequency response. Hence, in this paper, by using the FELMS algorithm in the conventional hybrid ANC system, a psychoacoustic hybrid ANC system was proposed, which can improve the system's noise reduction capability from psychoacoustic point of view. Also, the proposed ANC system can control both the correlated primary noise and uncorrelated disturbance. Loudness is used as the psychoacoustic criterion for evaluating the system's noise reduction performance. Simulation results show the superior performance of the proposed psychoacoustic hybrid ANC system over both the conventional hybrid ANC system and conventional psychoacoustic ANC system.

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