Psychoacoustic Active Noise Control System with Auditory Masking

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Abstract— **In practical active noise control (ANC) applications, it is difficult to completely cancel out the undesired noise. In order to improve the user's comfort level in a noisy environment, a psychoacoustic ANC system that incorporates masking techniques is proposed in this paper. A two-stage approach of performing ANC, followed by masking the residual noise with carefully selected masking signal, is used to enhance the user's listening experience. In order to mask the residual noise effectively, an automatic gain controller (AGC) is used to give different gains to the masking signal according to the residual noise level. A new mechanism to control the gain of the AGC is proposed so that the system can produce a conclusive listening experience for the user. The proposed hybrid ANC-masking system also takes into account of any uncorrelated noise that is only captured by the error microphone. Computer simulations are conducted to show the superior performance of the proposed psychoacoustic ANC system. Two real-signal cases are also considered in this paper to test out the effectiveness in combining ANC with masking.**

I. Introduction

Active noise control (ANC) [1, 2] is a well-developed technique for the purpose of reducing low-frequency acoustic noise, usually below 500 Hz. Traditional passive methods, such as enclosures, barriers and silencers, are bulky, costly and ineffective for this type of noise. ANC is based on the principle of superposition and aims to cancel out the undesired acoustic noise, which is also referred as the primary noise, by generating an "anti-noise" that has equal amplitude and opposite phase with reference to the primary noise. Therefore, when this anti-noise is combined with the primary noise, both noises are destructively interfered and thus cancelled out.

In many practical ANC applications, the primary noise produced by the rotating machines, such as engines, compressors, motors, fans and propellers, is periodic in nature and thus contains multiple tones at the fundamental frequency and several harmonic frequencies. In this case, the reference microphone can be replaced by a non-acoustic sensor, such as a tachometer or an accelerometer [3] to synchronize an internally generated reference signal. In this manner, the feedback from the secondary source to the reference sensor can be prevented.

Theoretically speaking, ANC is supposed to reduce the undesired noise to zero. However, in practical applications, due to many constraints, the undesired noise can only be reduced to an empirical minimum. This residual noise is still perceivable and can be quite annoying to the user, especially after the user's ears get adapted to it. It is very difficult to further reduce this residual noise to a lower level by reapplying ANC techniques. Therefore, instead of further reducing it, a pleasant audio signal, which is also referred as the masking signal, is introduced to the ANC system. This masking signal is utilized to mask the residual noise, so that the user will only be able to hear the pleasant masking signal. In this way, the user's comfort level in a noisy environment is improved.

In [4], Snehitha proposed an improved snore ANC system that provides a more conclusive environment for the non-snore-partner, by making use of psychoacoustic masking. In [5], Kierstein proposed a different type of psychoacoustic ANC system, in which the psychoacoustic masking is applied to reduce the human perception of a noise signal. But this method alters the shape of the masking signal, which can make the masking signal sound unpleasant. In [6], Doclo developed an ANC system using perceptual masking, which tries to shape the residual noise so that all its frequency components are below the masking threshold of the masking signal. But in practical applications, this system sometimes may not be able to shape the residual noise to the desired shape due to many constraints. In [7], Amit proposed an improved psychoacoustic ANC system based on the one developed in [4]. This improved system is targeting to control engine noise and an automatic gain controller (AGC) is added in to account for any variations in the characteristics of the undesired engine noise.

However, it is found that the system in [7] is developed based on the feedforward ANC structure, and thus only able to control the correlated noise generated by the user's own vehicle. The noises generated by other vehicles that are passing by may be detected only by the error microphone and uncorrelated with the reference signal and thus cannot be controlled. Hence, the residual noise level is high, due to the presence of the uncorrelated noise. Consequently, the AGC in the system will generate a high gain in order to mask this high-level residual noise. This can increase the volume of the masking signal significantly, which may not result in a good listening experience for the user.

Also, it is found that when new noise is detected by the ANC system, the gain of the AGC will increase abruptly, leading to a sudden increase in the volume of the masking signal. Additionally, the gain of the AGC will still be varying

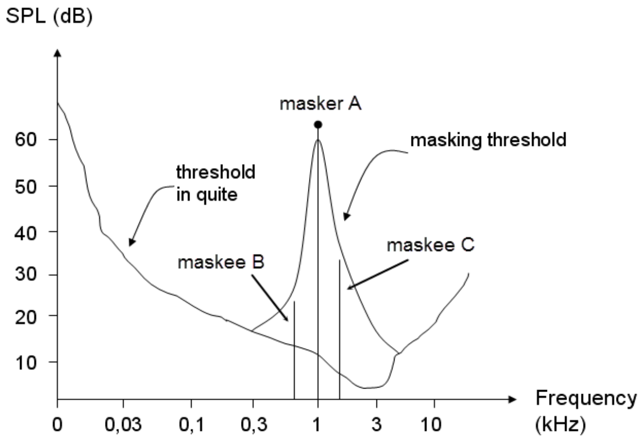

Fig. 1 Frequency masking (Adapted and modified from Wikipedia)

even after the convergence of the adaptive filter and the residual noise level has already been maintained. This is because the frequency spectrum of the masking signal may be varying, leading to variation in the masking capability of the masking signal during the replay process of the masking signal. Hence, the masking signal may no longer be pleasant to the user any more due to the variation in the volume of the masking signal. In this case, the user's listening experience will be badly impacted.

Therefore, considering the two problems mentioned above, we propose a new mechanism to control the gain of the AGC. A threshold is imposed on the variation of the gain so that the volume of the masking signal never changes abruptly, but gradually. In [8] and [9], hybrid ANC system [10] has been used to control the uncorrelated noise that appears in practical ANC applications. Here, hybrid ANC structure is also introduced to control both correlated noise generated by the user's own vehicle and uncorrelated noises generated by other vehicles.

The rest of this paper is organized as follows. In Section II, the basic principle of psychoacoustic masking is introduced. This is followed by the introduction of the proposed psychoacoustic ANC system in Section III. Section IV shows the computer simulation results of using the proposed psychoacoustic ANC system under different practical noisy environments, and its performance compared with the ANC system proposed in [7].

II. Psychoacoustic Masking

In order to provide a better understanding of the psychoacoustic masking phenomenon, human's perception of sound with respect to frequency masking [11] is presented in this section.

It is of common knowledge that louder sound masks softer sound. For example, a loud-engine truck moving on a street causes your phone conversation inaudible. This is an example of simultaneous masking, which is also referred as frequency masking. In this paper, frequency masking is used to mask out the residual noise. As shown in Figure 1, tone A is louder and thus can be considered as a masker for tones B and C.

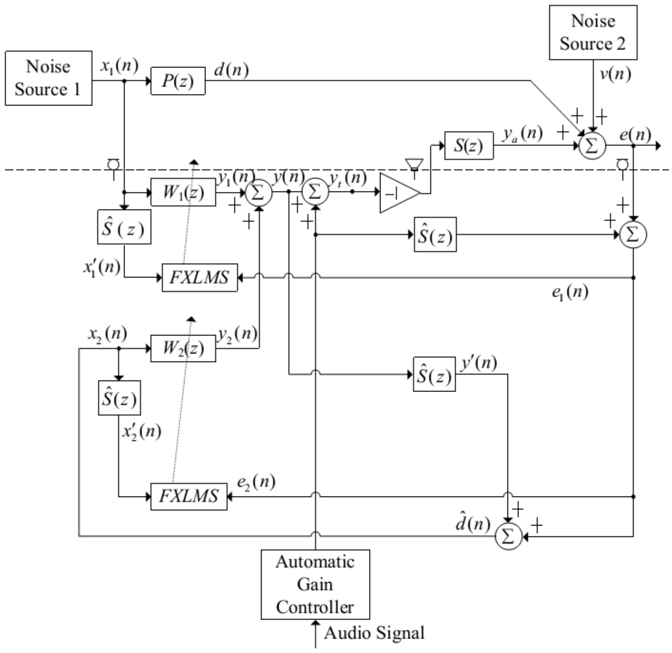

Fig. 2 Block diagram of the proposed psychoacoustic ANC system

Together with the threshold of quiet, the masking curve of tone A determines the audibility threshold for tones B and C. Any frequency components falling under the masking curve of A will not be perceived. The phenomenon of frequency masking occurs because of the excitation caused by the masker in the basilar membrane, which prevents the detection of the excitation in the same area of the basilar membrane from other softer sounds [12].

The masking capability of a tone signal in fact covers a particular frequency range. This range can be illustrated by the masking curve, which is also described by the masking function and dependent on the frequency and amplitude of the masker. The simplest masking function [11] is a triangular function with a steep slope for the lower frequencies and a gentler slope for the higher frequencies. But to be more precisely, spreading functions are sophisticated and highly nonlinear. In Figure 1, Schroeder spreading function is employed in order to generate the masking curve for tone A, which is given as [12]:

$$\begin{aligned} 10\log_{10} F(dz) &= 15.81+7.5(dz+0.474) \\ &\quad -17.5[1+(dz+0.474)^2]^{1/2}, \end{aligned} \tag{1}$$

where dz is the Bark scale difference between the frequencies of the maskee (softer tones) and the masker (louder tone).

III. Proposed Psychoacoustic ANC System

In order to improve the performance of the system in [7] when there is uncorrelated noise present, a hybrid ANC system is utilized, which consists of both feedforward and feedback adaptations. The feedforward adaptive filter is used to control the correlated noise level, while the feedback adaptive filter is used to cancel the uncorrelated noise based on an internally generated reference signal. The block

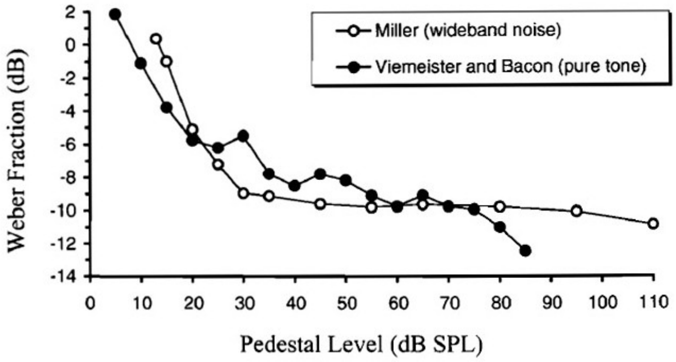

Fig. 3 Relationship between Weber Fraction and Pedestal Level (Adapted from [13])

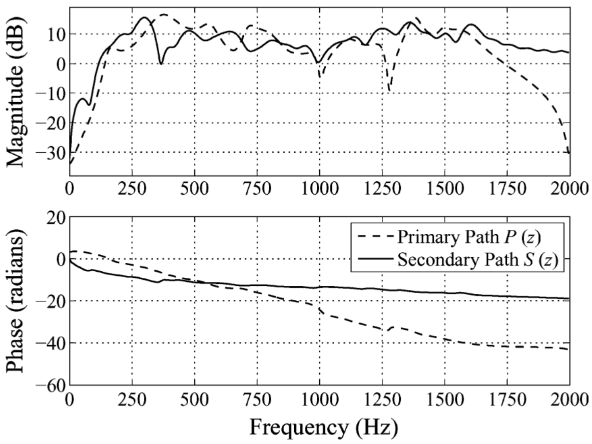

Fig. 4 Frequency response of the primary path $P(z)$ and secondary path $S(z)$

diagram of the proposed psychoacoustic hybrid ANC system is shown in Fig. 2.

The selection of the masker signal is very important since it directly determines the user's listening experience. The three conditions that the masker signal should satisfy are:

A. The residual noise should be transparent to an average listener with the masking signal present.

B. The masking signal should be played at the lowest volume possible.

C. The masker should sound pleasant to the listener.

The masker selection process proposed in [7] can be further simplified as below. Firstly, the sound pressure level (SPL) of the residual noise is calculated. Then the masking threshold of each potential masker for all relevant bands is calculated and compared with the residual noise SPL. After that, keeping the maskee amplitude constant, the energy for each masker is calculated. In the end, the masker with the least energy is ranked highest.

Let $X=\left(x_1,\ldots,x_n\right)$ be the maskee with its n frequency components, $Y_j=\left(y_1,\ldots,y_n\right)$ be a potential masker with corresponding n frequency components, and $\left[Y_1,\ldots,Y_m\right]$ be the set of all potential maskers. The matching process for Y_j and X is as follows:

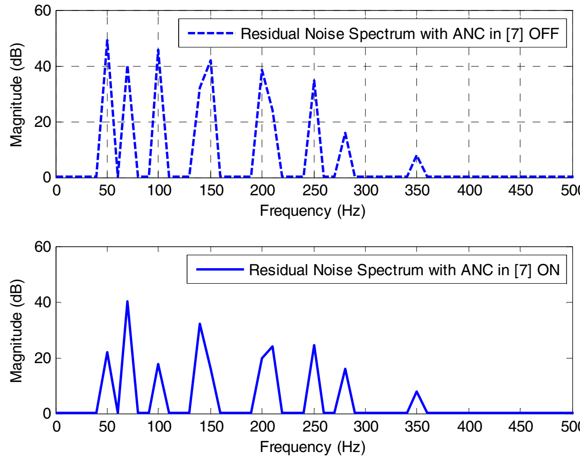

Fig. 5 Residual noise spectrum before and after the ANC system in [7]

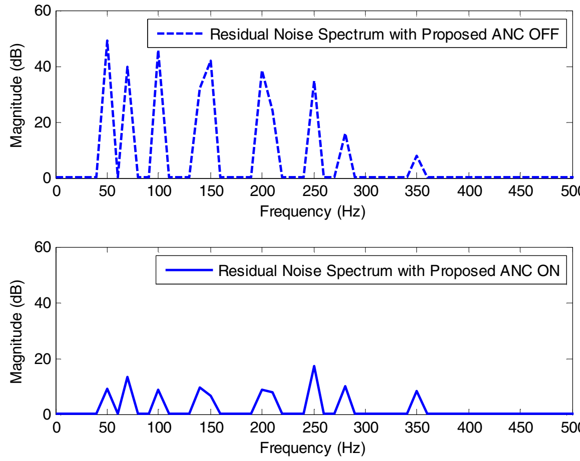

Fig. 6 Residual noise spectrum before and after the proposed psychoacoustic ANC system

Step 1: Compare the amplitude of Y_j with X and mark the largest difference between Y_j and X as $G_j=\max\left(Y_j-X\right)$.

Step 2: Increase the gain of Y_j by G_j.

Step 3: Again calculate $D_j=Y_j-X$.

Step 4: Calculate the masking score for all the potential maskers $S_j=\sum_{i=1}^{n} d_i$, where d_i is the i$^{\text{th}}$ component of D_j.

In the proposed psychoacoustic ANC system, there are two adaptive controllers, the feedforward adaptive filter $W_1(z)$ and the feedback adaptive filter $W_2(z)$. The correlated noise $d(n)$ is controlled by $W_1(z)$ based on the reference signal $x_1(n)$, which is synchronized through a non-acoustic sensor. The uncorrelated noise $v(n)$ is controlled by $W_2(z)$ based on the reference signal $x_2(n)$, which is internally synthesized according to the error signal $e(n)$ and the estimated anti-noise $y'(n)$. The coefficients of the two adaptive filters $W_1(z)$ and $W_2(z)$ are updated as follows:

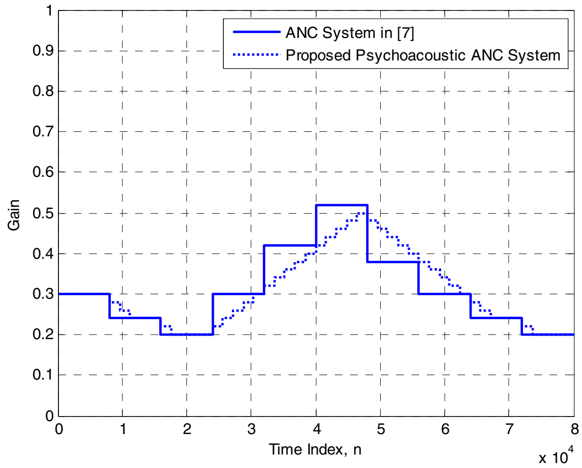

Fig. 7 Variation of AGC's gain in the ANC system in [7] and the proposed psychoacoustic ANC system

$$\mathbf{w}_1(n+1)=\mathbf{w}_1(n)+\mu_1\mathbf{x}_1'(n)e_1(n),$$
$$\mathbf{w}_2(n+1)=\mathbf{w}_2(n)+\mu_2\mathbf{x}_2'(n)e_2(n), \quad (2)$$

where $\mathbf{w}_1(n)$ and $\mathbf{w}_2(n)$ are the filter coefficients for the feedforward adaptive filter and feedback adaptive filter respectively, μ_1 and μ_2 are the step sizes, $\mathbf{x}_1'(n)$ and $\mathbf{x}_2'(n)$ are the filtered reference signals, and $e_1(n)$ and $e_2(n)$ are the error signals.

The accuracy of the secondary path model $\hat{S}(z)$ plays an important role in ANC system. Usually, white noise is used as the training signal to obtain the secondary path model, as white noise covers a wide range of frequency spectrum. However, white noise does not sound pleasant to the user. In [7], it has been found that the masking signal can also be used for training, which is pleasant to the user and in the mean time does not lead to any significant reduction in the system's performance. Hence, in this paper, the selected masker signal is also used as the training signal to obtain an accurate secondary path model.

It is found that music signal is usually a good choice for the masking signal because every person has his own favorite songs and those music signals must be pleasant to the user. At the same time those music signals are also able to mask the residual noise left in the ANC system so that the user will only hear the pleasant music. However, although the residual noise is maintained at a relatively stable level after the ANC system has converged, the music signal is non-stationary. Sometimes, there are very soft pieces and even silences. In these cases, if the ANC system in [7] is used, the gain of the AGC will be adjusted to a different value in order to mask the residual noise. Hence, the volume of the music will be changing, resulting in a very bad listening experience for the user. In fact, the AGC's gain will keep on changing because the frequency spectrum of the music keeps on changing along the time. This is not desired.

Also, when there is new noise detected by the ANC system, the overall residual noise level will be increased before the ANC system is able to make any responds. Before the noise is

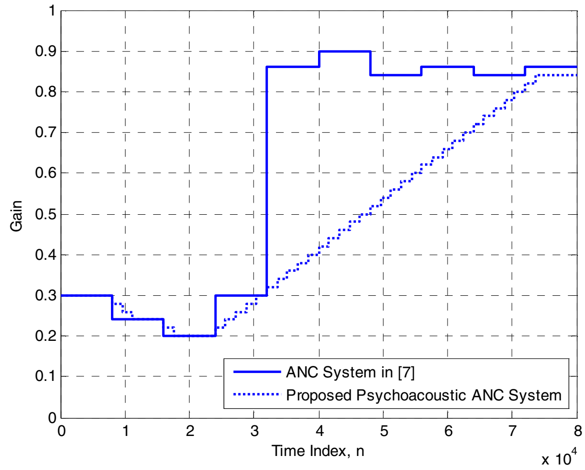

Fig. 8 Variation of AGC's gain in the ANC system in [7] and the proposed psychoacoustic ANC system when there is a new noise detected by the system

attenuated by the ANC system, the gain of the AGC will be increased significantly in order to make the masking signal loud enough to mask the increased residual noise. In this case, the volume of the masking signal will be increased abruptly, which is not desired.

Hence, in the proposed psychoacoustic ANC system, a threshold is imposed on the variation of the gain so that the volume of the masking signal never changes abruptly, but gradually. The purpose here is to make the variation of the masking signal's volume as small as possible so that the user does not perceive much change in the volume of the masking signal. In this way, the user's listening experience is maintained. Hence, the concept of just noticeable difference (JND) is applied here. JND [13], also known as the difference threshold, is the minimum difference in stimulation that a person can detect 50 percent of the time. JND is about 3 dB at the threshold of quiet and 1 dB for soft sounds around 30-40 dB at low and midrange frequencies. It may drop to 0.2 to 0.5 dB for loud sounds. The relationship between JND and sound intensity is shown in Fig. 3 and by Weber's law as below

$$\text{JND}=k.I, \quad (3)$$

where k is a constant, and I is the sound intensity. However, this is not precisely the case when it comes to the way how human beings perceive sound intensity changes at different starting intensity levels. This departure from Weber's law is known as Weber's law 'near miss' [14]. In this paper, JND is set as 1 dB for all frequency range and loudness level to simplify its implementation and results in relatively good performance.

Therefore, by setting JND as the threshold of the variation of the AGC's gain, which is 1 dB, the user will be able to hear a soothing and pleasant audio signal, whose volume varies in a minimum manner. In the proposed psychoacoustic ANC system, the AGC's gain adjustment is always below certain value so that the volume variation in the masking signal does not exceed JND. In this manner, the user will not be able to detect the variation in the volume of the masking signal,

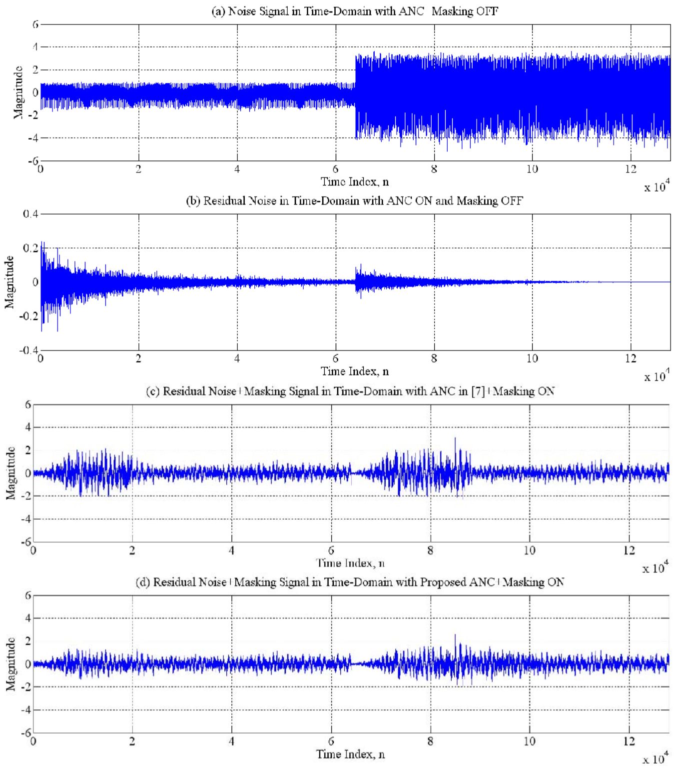

Fig. 9 Residual noise in time-domain with ANC OFF and ON and residual noise with masking signal with ANC system in [7] ON and proposed ANC system ON for the first real-signal case

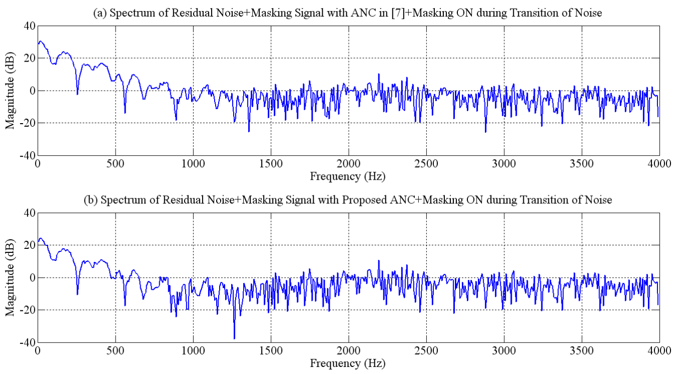

Fig. 10 Spectra of residual noise with masking signal with the ANC system in [7] ON and proposed ANC system ON during the transition of Noise for the first real-signal case

which is considered as a better listening experience for the user.

IV. Simulation Results

Computer simulations are conducted to verify the performance improvement of the proposed psychoacoustic ANC system. Since engine noise consists of tones at the fundamental frequency and several harmonics, in this paper it is assumed that the correlated noise contains narrowband noise at 50 Hz, 100 Hz, 150 Hz, 200 Hz and 250 Hz. The uncorrelated noise contains narrowband noise at 70 Hz, 140 Hz, 210 Hz, 280 Hz and 350 Hz. The frequency response of the primary path $P(z)$ and secondary path $S(z)$ are shown in

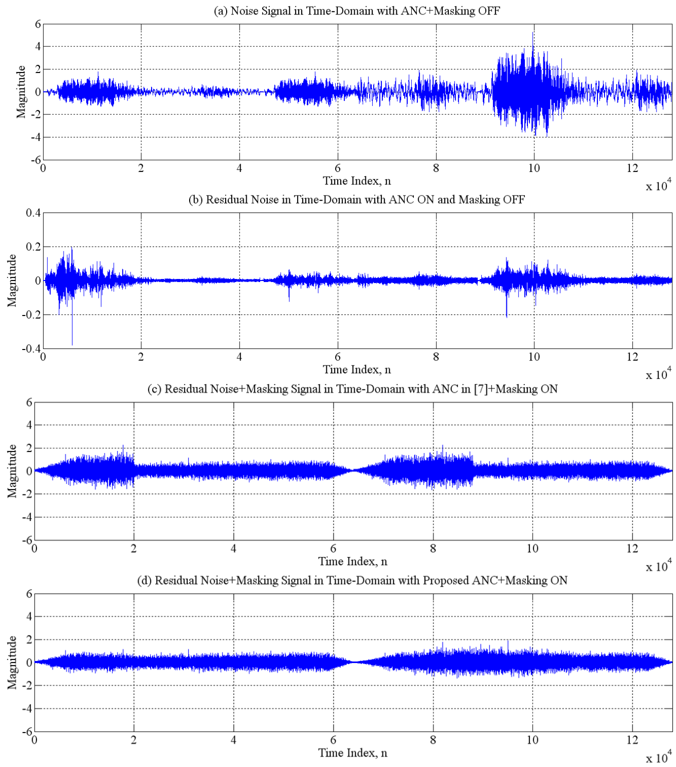

Fig. 11 Residual noise in time-domain with ANC OFF and ON and residual noise with masking signal with ANC system in [7] ON and proposed ANC system ON for the second real-signal case

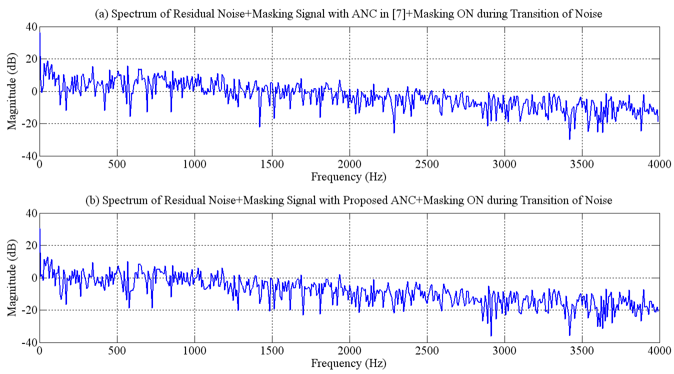

Fig. 12 Spectra of residual noise with masking signal with the ANC system in [7] ON and proposed ANC system ON during the transition of Noise for the second real-signal case

Fig. 4. The two adaptive filters used in the proposed psychoacoustic ANC system are both of length 32.

The frequency spectrum of the noise before and after using the ANC system in [7] is shown in Fig. 5 and the frequency spectrum of the noise before and after using the proposed psychoacoustic ANC system is shown in Fig. 6. It can be seen clearly that in Fig. 5 only the correlated noise is reduced. The two uncorrelated noises remain the same. However, in Fig. 6 both the correlated and uncorrelated noises are reduced in the proposed psychoacoustic ANC system.

Regarding the problem of variation of the AGC's gain, two cases are considered. One is due to the variation of the masking signal in the time-domain, resulting in a continuous variation in the volume of the masking signal. The other is due to the detection of a new noise, resulting in a sudden increase in the volume of the masking signal.

The variations of the AGC's gains in the ANC system in [7] and the proposed psychoacoustic ANC system during the replay of the music song are shown in Fig. 7. It is found that the gain in the ANC system in [7] keeps on changing abruptly because the frequency spectrum of the music signal keeps on changing along the time. However, in the proposed psychoacoustic ANC system, the AGC's gain gradually changes, resulting in a smooth change in the volume of the music and thus, a better listening experience for the user.

In Fig. 8, it is found that the ANC system in [7] responds very quickly, resulting in a sudden increase in the gain of the AGC. Hence, the volume of the masking signal will also be increased abruptly, which is not a good listening experience for the user. For the proposed psychoacoustic ANC system, the AGC's gain varies so that the volume of the masking signal varies in a minimum manner. In this way, the user can hardly detect the change in the volume of the masking signal. Therefore, a good listening experience for the user is achieved.

Figures 9 and 10 show a real-signal example of using ANC and masking to control an engine noise and masking the residual noise with an air-conditioner noise in time-domain and frequency-domain, respectively. Subplot 9(a) shows the engine noise being picked up from the start and switches to another speed at the iteration of 6.4×10^4. The time-domain error signal after ANC system has converged with no masking is plotted in subplot 9(b). Subplots 9(c) and 9(d) show the residual noise with masking signal in time-domain using system proposed in [7] and in this paper, respectively. Their respective spectra are shown in subplots 10(a) and 10(b) at the time frame after the transition at 6.4×10^4 with an FFT length of 1024. It can be clearly observed that the overall spectrum from the proposed system is lowered compared to that proposed in [7]. An air-conditioner noise signal was chosen in this experiment as the masking signal and played back from the secondary loudspeaker. Studies [15-17] have shown that the air-conditioner noise sounds like white noise, which can help people to relax and concentrate. There are also some other signals, such as natural sounds like waterfall and bird sound that are considered as good masking sound.

Figures 11 and 12 show another real-signal example of using ANC and masking to control a snore noise and using a masking sound of raining signal to mask out the residual noise. Again, it was found that the proposed psychoacoustic ANC system was able to generate a more gradual change in the volume of the masking signal as compared with the system in [7], although both systems reduced the noise to the same level.

V. CONCLUSIONS

In this paper, an improved psychoacoustic ANC system was proposed, which incorporates the technique of psychoacoustic masking into ANC system. Simulation results showed that the proposed psychoacoustic ANC system was able to control both the correlated and uncorrelated noise based on a hybrid ANC structure. The proposed system also produces a more conducive listening experience for the user in a noisy environment because of the new control mechanism of the AGC's gain, which varies in a minimum manner so that the user can hardly detect the variation in the volume of the masking signal. This can be clearly seen in the two real-signal cases of canceling engine noise and using air-conditioner signal as the masker, and attenuating snore noise with raining signal as the masker. One problem with the proposed system is that sometimes it may react too slowly to the variation in the noise signal. This can be solved by providing variable thresholds for the AGC gain control and will be implemented in future design. Another area of research area is to study the human preference of different types of masker to mask different types of noise signatures.

REFERENCES

[1] S. M. Kuo and D. R. Morgan, *Active Noise Control Systems – Algorithms and DSP Implementations*, New York: Wiley, 1996.

[2] S. M. Kuo and D. R. Morgan, "Active noise control: A tutorial review," *Proc. IEEE*, vol. 8, no. 6, pp. 943-973, Jun. 1999.

[3] G. W. B. Chaplin, "The cancellation of repetitive noise and vibration," in *Proc. Inter-Noise*, Dec. 1980, pp. 699-702.

[4] Snehitha Singaraju and Sen M. Kuo, "Noise masking using psychoacoustics," in *Proc. Active 06*, Sep. 2006.

[5] Kierstein Laukofoed and Eskildsen Jørn, "A system for providing a reduction of audiable noise perception for a human user," Patent WO 2007/038922 A1, April 12, 2007.

[6] Doclo Simon, "Active noise reduction method using perceptual masking," Patent EP 2 284 831 A1, Feb 16, 2011.

[7] Amit Rajora, Woon-Seng Gan, Sen M. Kuo and Yong-Kim Chong, "Noise suppression using active noise control and masking," in *Proc. 14th Int. Congress on Sound & Vibration*, July 2007.

[8] Muhammad Tahir Akhtar and Wataru Mitsuhashi, "Improving Performance of Hybrid Active Noise Control Systems for Uncorrelated Narrowband Disturbances," *IEEE Trans. On ASLP*, vol. 19, no. 7, Sep 2011.

[9] Tongwei Wang, Woon Seng Gan and Yong Kim Chong, "Psychoacoustic Hybrid Active Noise Control System," in *Proc. ICASSP*, 2012.

[10] D. C. Swanson, "Active noise attenuation using a self-tuning regulator as the adaptive control algorithm," in *Proc. Inter-Noise*, pp. 467-470, 1989.

[11] H. Fastl and E. Zwicker, *Psychoacoustics: Facts and Models (3rd Edition)*, Springer, 2006.

[12] M. Bosi, *Introduction to Digital Audio Coding and Standards*, Springer, 2002.

[13] Christopher J. Plack, The Sense of Hearing, Erlbaum, 2005.

[14] Thomas Augustin and Tanja Roscher, "Empirical evaluation of the near-miss-to-Weber's law: a visual discrimination experiment," *Psychology Science Quarterly*, Volume 50, 2008 (4), pp. 469-488

[15] http://www.sleepfoundation.org/article/how-sleep-works/the-sleep-environment

[16] http://www.spiritmag.com/features/article/the_science_of_zzzzzzzs/

[17] http://whitenoisemp3s.com/sounds-like/air-conditioner