Active Snore Control System Integrated with Apnea Detector

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ABSTRACT

This paper presents a snore active noise control (ANC) system to effectively reduce the loud snore for the snorer's bed partner. Real-time experiments are conducted to evaluate the noise reduction performance based on the headboard and pillow setups. This snore ANC system is integrated with a non-obtrusive technique to detect obstructive sleep apnea (OSA) of the snorer. The OSA detection is based on the bispectral analysis of the snore signals picked up by the reference microphone of ANC system.

Keywords: Active noise control, FXLMS algorithm, Snore, Sleep apnea detection, Bispectral analysis
I-INCE Classification of Subjects Number(s): 37.7

1. INTRODUCTION

Snoring is a common sleep disorder, about one third of adult population snore. Snoring can be so loud to keep the snorer's bed partner awake and make sleep less restful. Snoring can also cause significant psychological and social damage to both the snorers and their bed partners, resulting in separate bedrooms, conflicts, etc. In addition, snoring can result in daytime drowsiness, irritability and reduced alertness, and may cause hearing problems to the snorer's bed partner [1].

Active noise control is effective of canceling low-frequency noise based on the acoustic principle of superposition of the primary noise with the generated anti-noise, which has the same amplitude but opposite in phase of the primary noise. Since most dominant frequency components of snore are below 2 kHz, an ANC system can be applied to effectively reduce the snoring noise for the snorer's bed partner.

The snore ANC system developed in [2] is installed on a headboard, where the two error microphones and two secondary loudspeakers are mounted on the headboard. Unfortunately, some headboards are difficult to install, not portable, and some beds even without headboard. Furthermore, the quiet zone generated by the ANC is centered at the error microphones on the headboard, which is far away from the ears of the snorer's bed partner, results in lower noise reduction at the ears. To solve these problems, the technique developed in [3] places the error microphones inside the pillow below

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the ears of the sleeper, which ensures that the error microphones are close to the ears. Furthermore, since the secondary loudspeakers are also placed inside the pillow, thus requires lower volume of anti-noise, and results in reduced acoustic feedback to the reference microphone. Other benefits are that the pillow is portable, and easy to apply at different applications such as headrests.

Sleep apnea is a sleep disorder characterized by pauses in breathing during sleep. A sleep study or polysomnogram (PSG) is the most accurate test for diagnosing sleep apnea, which is usually performed in a sleep lab. However, the cost of PSG is very high, the testing is highly uncomfortable as it involves multiple head, face, and body electrodes. Furthermore, people have to wait for the assessment, and just know if they have OSA. These problems motivated researchers to look for simple and portable monitoring devices/methods that can detect obstructive sleep apnea and make real-time assistance if needed when the OSA occurs.

This paper uses the two-dimensional frequency analysis of snore signals to detect OSA [4]. The detector uses the primary microphone of the snore ANC system to sense the snore and then uses the bispectral analysis to detect if it is just a snore or an OSA. This technique is non-obtrusive because it doesn't restrict the snorer from physical activity and doesn't disturb the sleep. This method can be integrated with the snore ANC system without any additional cost as the apnea detection algorithm is implemented on the same digital hardware for the snore ANC.

The rest of paper is organized as follows. Section 2 briefly introduces a multiple-channel ANC algorithm and its installation on a headboard and a pillow. The real-time experiments of the snore ANC systems based on the headboard and pillow setups are presented in Section 3. Section 4 introduces bispectral analysis to detect obstructive sleep apnea.

2. SNORE ANC SYSTEMS AND SETUPS

2.1 Introduction to ANC Algorithm

A feedforward ANC system uses reference microphone(s) to sense the primary noise to be canceled, while an adaptive feedback ANC system synthesizes the reference signal [5]. Feedforward ANC is generally more robust than feedback ANC, particularly when the reference sensor can be isolated from the secondary source(s) for reducing acoustic feedback. Because of the nonstationary characteristics of snore [2], we use feedforward ANC systems to reduce the snoring noise.

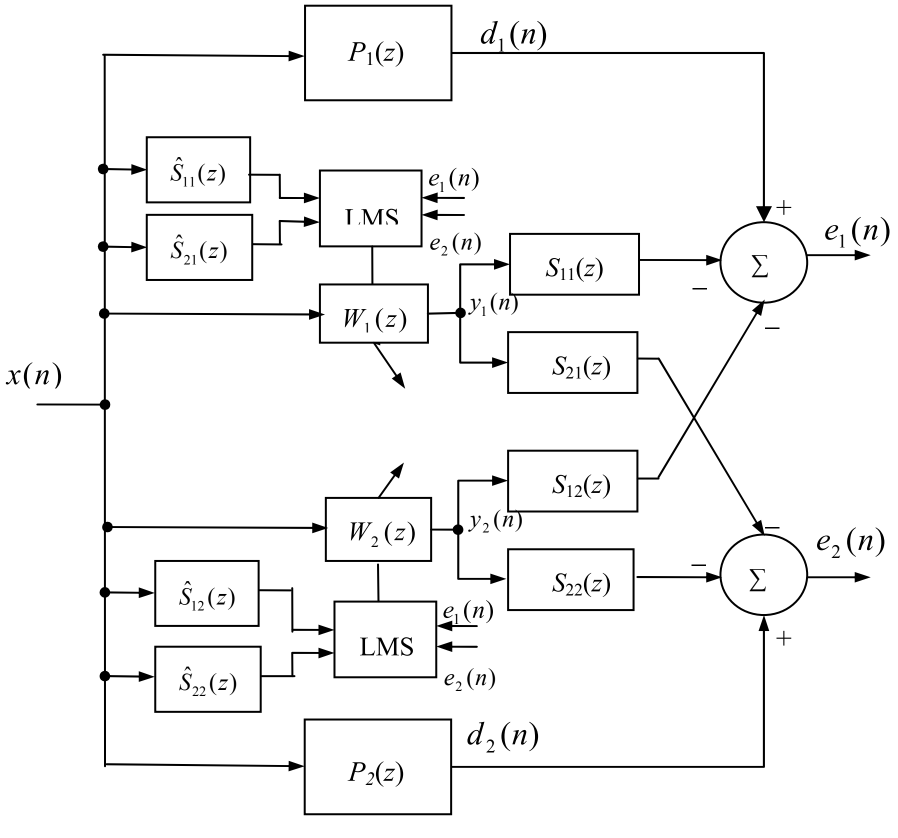


Fig. 1 Block diagram of multi-channel ANC system using the 1x2x2 FXLMS algorithm.

The block diagram of multi-channel feedforward ANC system using the 1x2x2 (one reference sensor, two secondary sources, and two error sensors) filtered-x least mean square (FXLMS) algorithm is shown in Fig. 1, where $x(n)$ is the reference signal picked up by the reference sensor, $d_1(n)$ and $d_2(n)$ are the primary noises to be canceled, and $P_1(z)$ and $P_2(z)$ are the unknown primary paths [5]. The adaptive filters $W_1(z)$ and $W_2(z)$ generate the anti-noise, $y_1(n)$ and $y_2(n)$, respectively, which are output to drive the corresponding secondary loudspeakers. The secondary paths $S_{11}(z)$ and $S_{21}(z)$ are from $y_1(n)$ to the two error sensors, and $S_{12}(z)$ and $S_{22}(z)$ are the secondary paths from $y_2(n)$ to the two error sensors, $\hat{S}_{ij}(z)$ (for i=1,2 and j=1,2) is the estimate of the corresponding secondary path, $S_{ij}(z)$, and $e_1(n)$ and $e_2(n)$ are the error signals picked up by the error sensors.

The adaptive weight vectors are updated by the 1x2x2 FXLMS algorithm expressed as

$$\mathbf{w}_1(n+1) = \mathbf{w}_1(n) + \mu_1\{[\hat{s}_{11}(n) * \mathbf{x}(n)]e_1(n) + [\hat{s}_{21}(n) * \mathbf{x}(n)]e_2(n)\}, \tag{1}$$

$$\mathbf{w}_2(n+1) = \mathbf{w}_2(n) + \mu_2\{[\hat{s}_{12}(n) * \mathbf{x}(n)]e_1(n) + [\hat{s}_{22}(n) * \mathbf{x}(n)]e_2(n)\}, \tag{2}$$

where * denotes linear convolution, $\mathbf{x}$(n) is the reference signal vector, μ_1 and μ_2 are the step sizes for updating the adaptive filters $W_1(z)$ and $W_2(z)$, respectively, $\hat{s}_{11}(n)$, $\hat{s}_{12}(n)$, $\hat{s}_{21}(n)$, and $\hat{s}_{22}(n)$ are the impulse responses of the secondary-path estimation filters $\hat{S}_{11}(z)$, $\hat{S}_{12}(z)$, $\hat{S}_{21}(z)$, and $\hat{S}_{22}(z)$, respectively.

2.2 Snore ANC Setups

Fig. 2. Experimental setup of the snore ANC system based on the headboard.

The experimental setup of the snore ANC using a headboard was installed on a twin-size headboard as shown in Fig. 2 [2]. Two 6-1/2” loudspeakers are mounted on the headboard as the secondary sources for generating the canceling noise. These loudspeakers are tilted towards the snorer's bed partner. Two error microphones are also mounted on the headboard to pick up the residual noise. A model of a human torso called the KEMAR (Knowles Electronics Mannequin for Acoustics Research) is used as the bed partner who will be listening to the snoring noise. Two microphones installed inside the ear cavity of the KEMAR are used to evaluate the performance of the snore ANC at the ears of the bed partner. The primary noise source (snorer) is simulated by a loudspeaker that is used to play the recorded snore. This loudspeaker is placed in the same room (not shown in the figure). A reference microphone is also mounted close to the noise source to pick up the snoring noise.

The experimental setup of the multi-channel snore ANC system using the 1x2x2 FXLMS algorithm based on the pillow is constructed in [6]. In this setup, the two error microphones and the two secondary loudspeakers are placed inside the pillow, where the loudspeakers are located at the back corners of pillow and the error microphones are placed under the ears of sleeper. The dimension of the pillow used for the experiments is 19.5"x15.5"x5". The error microphones are located at the depth of about 1" inside the pillow, under the corresponding ears of the KEMAR. The secondary loudspeakers are located at the back corners of the pillow, about 8" away from the error microphones.

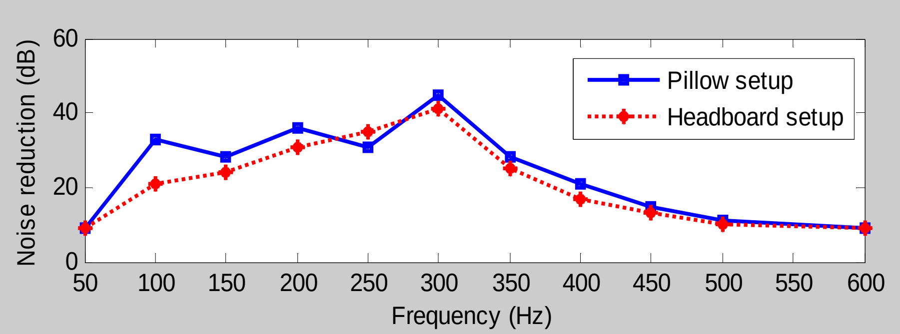
The distance between the left (or right) error microphone and the corresponding ear of the KEMAR for the headboard setup is about 2 feet; while the distance between the left (or right) error microphone and the corresponding ear of the KEMAR for the pillow setup is only about 4 inches. As the quiet zone produced by the ANC system is generally centered at the error microphones and the noise reduction decreased as we move away from the center of the quiet zone, the noise reduction at the ears of the KEMAR for the pillow setup is higher than the headboard setup.

3. EXPERIMENTAL RESULTS

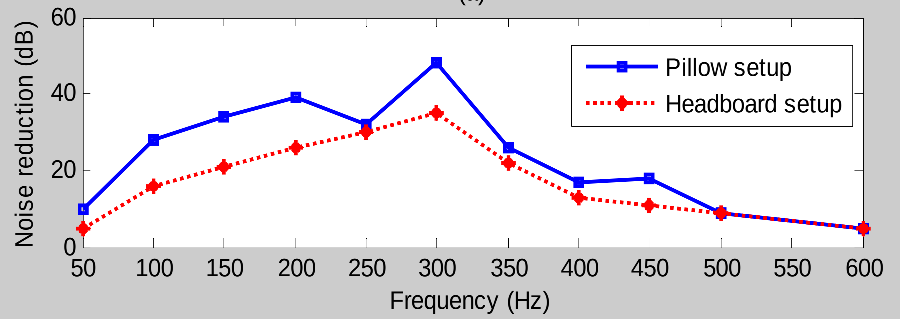
This section presents the experiment results of multi-channel snore ANC system using the 1x2x2 FXLMS algorithm. The system was tested using two experimental setups, one based on the headboard and the other based on the pillow [6]. We also used both sinusoids and recorded snore as the primary noise to evaluate snore ANC performance.

3.1 Tonal Noises

The multi-channel ANC system is first tested using sinusoidal primary noise with frequency varying from 50 Hz to 600 Hz at the step of 50 Hz. The noise cancellation achieved for both the headboard setup (dotted red line) and the pillow setup (solid blue line) is summarized in Fig. 3 for the right-side of microphones (see [6] for left-size results). Note that the noise cancellation at the error microphone (top figure) is higher than at the ear of the KEMAR (bottom figure) for the headboard setup; while the noise cancellation at these two microphones is similar for the pillow setup. These results show that in the pillow setup, the ears are close to the center of quiet zone. It is also observed that the achieved noise reduction for the pillow setup is higher than the headboard setup. This is because of the reduced distance between the secondary loudspeakers and the error microphones in the pillow setup as compared to the headboard setup.



(a)

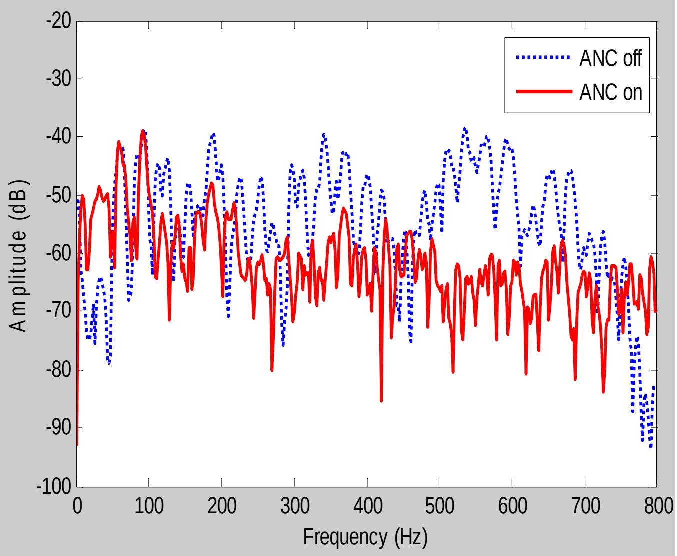


(b)

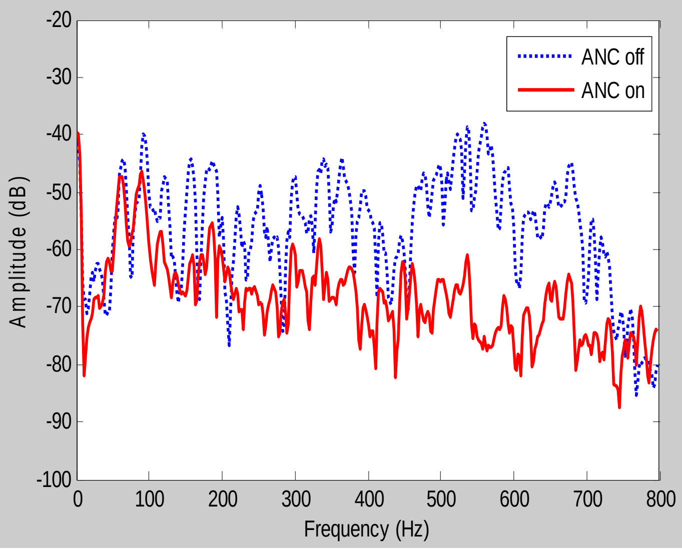
Fig. 3 Noise reduction for both the headboard and pillow setups at the right (a) error microphone and (b) ear of KEMAR.

3.2 Recorded Snore

The multi-channel snore ANC system is further tested using the recorded snore for both setups. As an example, spectra of error signals before and after ANC at the right ear of KEMAR for the (a) headboard setup and (b) the pillow setup are shown in Fig. 4. For the headboard setup, average noise reduction of 16 dB and 13 dB are achieved at the right error microphone and ear of the KEMAR, respectively. For the pillow setup, average noise reduction of 18 dB and 17 dB are achieved at the right error microphone and right ear of the KEMAR, respectively. It is observed that the noise cancellation for the pillow setup is higher than the headboard setup. Furthermore, it is observed that the noise reduction at the error microphones and the ears of the KEMAR is similar for the pillow setup, while the noise canceling performance at the ears of the KEMAR is lower as compared to that at the error microphones for the headboard setup.



(a)



(b)

Fig. 4 Spectra of signals at the right ear of KEMAR before and after ANC for (a) the headboard setup and (b) the pillow setup.

4. SLEEP APNEA DETECTION

4.1 Bispectral Analysis of Snoring Signals

Bispectral analysis shows a statistical nonlinear interaction in signals. Bispectral analysis effectively identifies the phase relationship of signals between different frequency bands [4]. Let $x(n)$ denotes the snore signal, the bispectrum of the signal is expressed as

$$B(f_1, f_2) = E\left[X(f_1)X(f_2)X^*(f_1+f_2)\right] \tag{3}$$

where f_1 and f_2 are the two frequencies at which the bispectrum is calculated, $E[.]$ represents the statistical expectation operation, $X(f)$ is the Fourier transform of $x(n)$, and $X^*(f)$ is the complex conjugate of $X(f)$.

The bispectrum is a symmetric function. In the bispectrum of the snore, the sharpest peak of an apnea snorer (snorer with sleep apnea) is located away from the origin, while the sharpest peak of a benign snorer (a snorer without sleep apnea) is located near the origin [4]. Furthermore, the bispectral amplitude of the apnea snore is higher than the benign snore because of the higher amount of non-linearity as compared to the benign snore. Based on these two facts, the bispectrum of snore signals can be used to detect sleep apnea from the sensed snore signals.

A MATLAB code to implement Equ. (3) is written to compute and plot the bispectrum of snore signal. From the bispectral plot, sleep apnea is detected based on the location of the sharpest peak and the amplitude of the bispectrum, which is indicated the side color bar. If the signal is a benign snore, the sharpest peaks in the bispectrum are close to the origin and will locate inside the detection circle defined by a given threshold value. If the peaks of the bispectrum are located within the detection circle, the snorer is classified as a benign snorer. However, for an apnea snorer, the sharpest peaks in the bispectrum would be away from the origin, thus the peaks are located outside the detection circle.

4.2 Simulation Results

The bispectrum analysis algorithm was tested using the snore episodes available from physionet.org, an open source database provided by MIT. The database consists of several snore episodes and their corresponding polysomnograms with sleep apnea annotations.

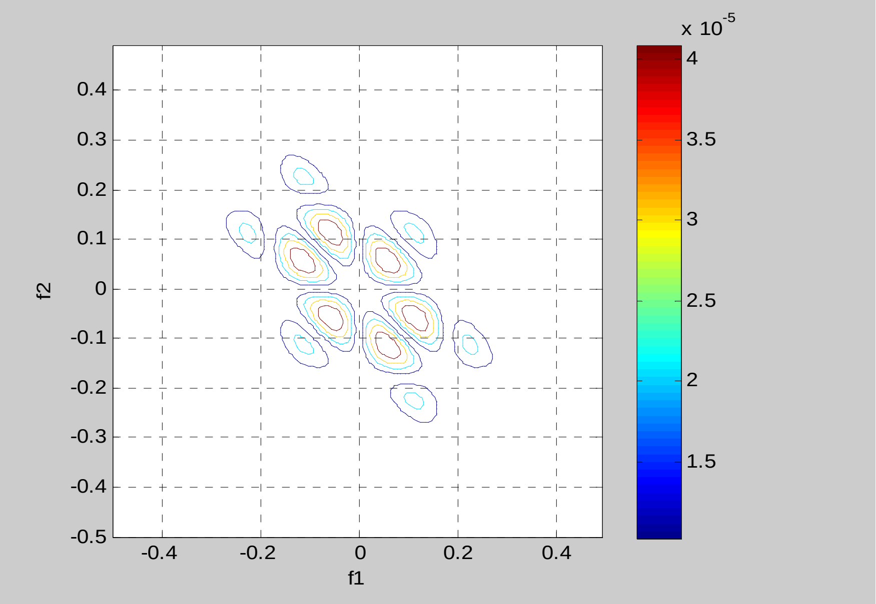


Fig. 5 An example of bispectrum plot of a benign snorer

Figure 5 shows an example of the bispectrum of snore signal from a benign snorer. The axes of the bispectrum are normalized frequencies f1 and f2, the sampling rate is 2 kHz. The peak of the bispectrum is the envelope with the highest bispectral amplitude. If the non-linearity in the signal is higher (an apnea snore), the signal has a high amplitude peak indicated by red. In Fig. 5, the peaks of the bispectrum correspond to the envelope in red are located in the normalized frequencies below 0.1 on both axes, inside the circle of 0.15.

Figure 6 shows the bispectrum of the snore signal from an apnea snorer. In this case, the positions of the peaks are away from the origin, between the normalized frequencies 0.2 and 0.4, outside the 0.15 threshold (circle). The amplitude of the peaks is more than 100 times the amplitude of the peaks observed in Fig. 5, indicated by the side color bar.

It is observed that in the bispectrum of snore signals, the peaks are located closer to the origin for a benign snorer; while the peaks are located away from the origin for an apnea snorer. Furthermore, it was found that the amplitudes of the peaks of the bispectrum are higher (in darker red) for an apnea snorer as compared to a benign snorer. This can be related to the fact that the degree of non-linearity in the frequency contents of an apnea snorer is higher than a benign snorer. This results in higher degree of coupling in apnea snorers and thus higher amplitudes of the peaks in the bispectrum.

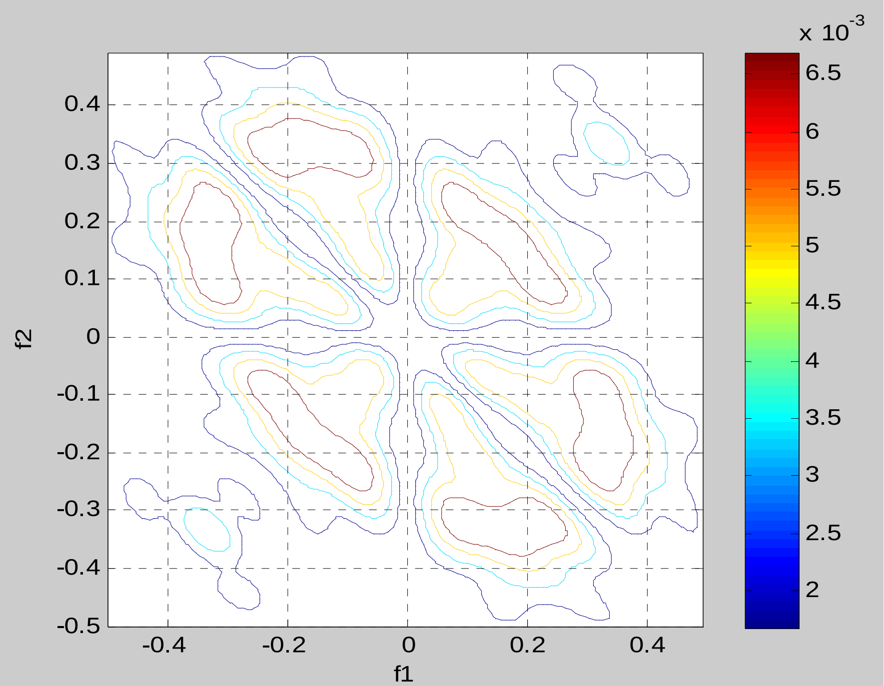


Fig. 6 Bispectrum plot of an apnea snorer

5. CONCLUSIONS

This paper developed the snore ANC system based on the pillow setup and integrated with the obstructive sleep apnea detector. This snore ANC pillow is effective in providing an ambient environment for the snorer's bed partner, while protecting him/her from the harmful snoring noise. The performance of snore ANC installed on both headboard and pillow setups were evaluated using real-time experiments. The snore ANC system was integrated (without additional hardware cost) with the sleep apnea detector to identify apnea using the bispectrum analysis of snore signals.

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