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Active Noise Control: Open Problems and Challenges

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Abstract—**This paper introduces active noise control (ANC) techniques focusing on challenges in developing practical applications and open problems for research from the signal processing perspective. We propose advanced strategies to further improve ANC performance that include virtual sensing, residual noise masking, and active sound quality control. We also present several challenges for real-world applications such as canceling high-frequency and impulse-like noises, and reducing noises generated from moving sources. Finally, ANC applications in consumer products and healthcare devices are used to demonstrate some potential add-on functions for promoting cost-effective ANC products.**

I. INTRODUCTION

Active noise control systems [1-6] cancel the undesired noise by generating a secondary noise of equal amplitude and opposite phase of the primary noise for the cancellation of both noises based on the principle of superposition. The ANC system is very effective for attenuating low-frequency noises where passive methods are expensive and ineffective. Most practical ANC systems use adaptive filters to automatically track variations of unknown noise characteristics and environment. The most commonly used adaptive filter is the finite impulse response (FIR) filter with the filtered-X least-mean-square (FXLMS) algorithm [7, 8]. The commercially available digital signal processors [9] simplified real-time experimentation of ANC algorithms, thus promoting development and application of ANC systems.

This paper briefly reviews basic ANC algorithms and proposes some open problems for further research from signal processing perspectives. We also present advanced techniques such as virtual sensing, residual noise masking, and active sound quality control to improve system performance for commercialization. In addition, we introduce some add-on functions to increase the overall value of ANC systems and make them more attractive and cost-effective for real-world applications.

II. ANC SYSTEMS AND OPEN PROBLEMS

The basic single-channel ANC system using the FXLMS algorithm is illustrated in Fig. 1 [2], where the reference signal $x(n)$ is picked up by a reference sensor. The reference signal is processed by the adaptive filter $W(z)$ to generate the canceling signal $y(n)$ driven by a secondary loudspeaker. The error sensor is used to monitor the ANC performance by sensing the residual noise $e(n)$. The use of the adaptive algorithms for ANC systems is necessary to compensate for the secondary path $S(z)$ [2].
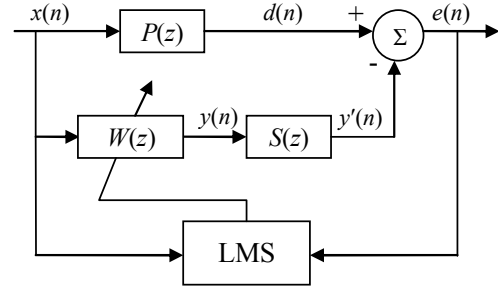

Fig. 1 Basic single-channel ANC system using the FXLMS algorithm

In this section, we use basic ANC algorithms to present some open problems for further research from adaptive signal processing viewpoints.

A. Broadband Feedforward Systems

As shown in Fig. 1, the secondary signal $y(n)$ is computed as [2]

$$y(n) = \mathbf{w}^T(n)\mathbf{x}(n), \qquad (1)$$

where $\mathbf{w}(n) = \begin{bmatrix} w_0(n) & w_1(n) & ... & w_{L-1}(n) \end{bmatrix}^T$ and $\mathbf{x}(n) = [x(n) \ x(n-1) \ ... \ x(n-L+1)]^T$ are the coefficient and signal vectors of $W(z)$, respectively, and L is the filter length. The FXLMS algorithm updates the coefficient vector as

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \mu\, \mathbf{x}'(n)e(n), \qquad (2)$$

where μ is the step size (or convergence factor) that determines the convergence speed,

$$\mathbf{x}'(n) = \hat{s}(n) * \mathbf{x}(n) \qquad (3)$$

is the filtered signal vector and $\hat{s}(n)$ is the impulse response of the secondary-path estimation filter, $\hat{S}(z)$.

The most popular filter structure used for ANC systems is the FIR filter given in (1). It can be replaced by infinite impulse response filters, lattice filters, transform-domain filters, subband filters, etc. [2]. The convergence rate of the

FXLMS algorithm given in (2) can be improved by using variable step sizes, recursive least square algorithms, affine projection algorithms, Kalman algorithms, etc. In addition, nonlinear adaptive filters with associated algorithms can be used to reduce nonlinear effects caused by different factors. It is still an area of open research to develop more advanced adaptive algorithms in order to further improve the performance of ANC systems.

The FXLMS algorithm expressed in (2) and (3) is very tolerant of errors made in the estimation of $S(z)$ by the filter $\hat{S}(z)$. Within the limit of slow adaptation, the algorithm will converge with nearly 90° of phase error between $\hat{S}(z)$ and $S(z)$. Therefore, off-line modeling can be used to estimate $S(z)$ during the initial training stage for most ANC applications, however, on-line modeling may be required for some applications that involves fast changing environments. The detailed procedure for off-line modeling and some on-line secondary-path modeling algorithms are summarized in [2]. The development of robust and efficient on-line secondary-path modeling algorithms still deserves further research. In particular, development of on-line modeling techniques without using additive noise is critical.

The acoustic ANC system shown in Fig. 1 uses a reference microphone to pick up the reference noise. Unfortunately, the anti-noise generated by the secondary loudspeaker also radiates upstream to the reference microphone, resulting in a undesired acoustic feedback that corrupts the reference signal $x(n)$. One solution for eliminating acoustic feedback is to use a feedback neutralization filter [2]. Since the primary noise is highly correlated with the anti-noise, the on-line adaptation of the feedback neutralization filter must be inhibited when the ANC system is in operation. Therefore, analysis on the effects of acoustic feedback and the development of effective on-line feedback-path modeling techniques still remains open for further research [11].

B. Narrowband Feedforward Systems

A narrowband ANC system uses an internally synthesized reference signal $x(n)$. Two types of reference signals are commonly used in narrowband ANC systems: (1) an impulse train with a period equal to the inverse of the fundamental frequency of the periodic noise [12], and (2) sinusoidal signals that have the same frequencies as the corresponding harmonic components [13].

A digital recursive quadratic oscillator generates two orthogonal cosine and sine components. These two signals are separately weighted and then summed to produce the canceling signal $y(n)$. In practical applications, periodic noise usually contains multiple narrowband components. This requires higher-order adaptive filters that can be implemented by using direct, parallel, direct/parallel, or cascade forms [2].

Analysis of narrowband ANC systems is usually based on a single-frequency case. The analysis and optimization of widely-used parallel and other forms for multiple-frequency cases is open for research. Also, analysis of using single error signal $e(n)$ to update multiple adaptive filters deserves further study and improvement. In addition, a narrowband ANC system assumes the reference signal $x(n)$ has the same

frequency as the primary noise $d(n)$ at the error sensor location. In many practical applications, the reference sinusoidal frequencies used by the adaptive filters may be different than the actual frequencies of primary noise. This frequency mismatch will degrade the performance of ANC systems, and these effects have been analyzed recently [14]; however, effective solutions remain to be developed for practical applications.

C. Adaptive Feedback ANC

A single-channel adaptive feedback ANC system synthesizes (or regenerates) the reference signal $x(n)$ based on the adaptive filter output $y(n)$ with the secondary-path model $\hat{S}(z)$ and the error signal $e(n)$. Thus, this technique is also known as internal model control [15]. We can estimate the primary noise $d(n)$ exactly if $\hat{S}(z) \approx S(z)$, and use this estimated primary noise as the reference signal $x(n)$. This adaptive feedback ANC algorithm has many advantages and can be applied in ANC headsets and other industrial applications [16].

There are many open problems for further study of adaptive feedback ANC systems. For example, what kinds of noises can be effectively reduced by the adaptive feedback ANC, the effects of secondary-path modeling error on the accuracy of synthesized primary signal $x(n)$ and the performance of the ANC system, and the stability and convergence rate of the systems.

III. CHALLENGES FOR IMPROVING ANC PERFORMANCE

Fig. 2 Experimental setup of the snore ANC system

In this section, we use the snore ANC system installed on a traditional headboard [17] as an example for presenting several challenges to further improve performance of ANC systems for practical applications. The snore ANC for the bed partner is shown in Fig. 2. Two secondary loudspeakers and two error microphones are mounted on the headboard. A model of a human torso called the KEMAR (Knowles Electronics Mannequin for Acoustics Research) is used as the bed partner. Two microphones inside the ear cavities of the KEMAR are used to evaluate the performance at the ears of

the bed partner, which mimics real performance perceived by the human.

The spectral plots of signals picked up by the error microphones and the microphones inside the ears of the KEMAR were obtained using an HP dynamic signal analyzer. These plots show the spectra of noises before (ANC OFF) and after (ANC ON) the operation of active snore cancellation.
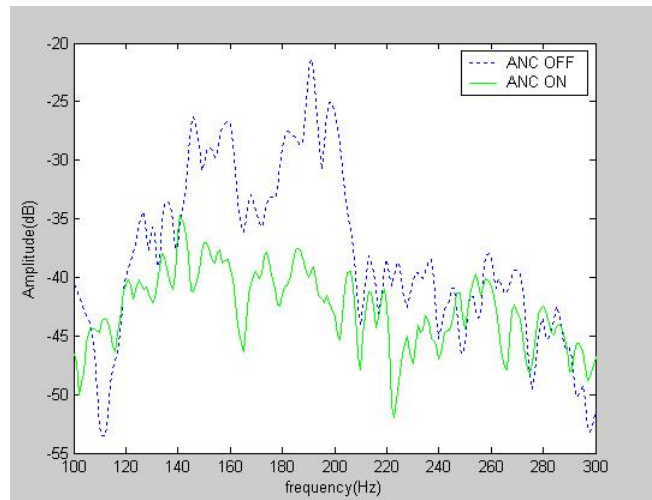

Fig. 3 Spectra of signals at the left error microphone

Figure 3 shows the spectra of snore signals picked up by the left error microphone before (original snore) and after (residual snore) the operation of ANC system. The average noise reduction is about 10-20 dB. Figure 4 shows the spectra of signals sensed by the microphone inside the left ear of the KEMAR. The average snore noise reduction is about 5-10 dB. These results clearly show that better ANC performance can be achieved by placing the error microphones close to the ears of KEMAR, especially at the high-frequency region that has a smaller quiet zone.
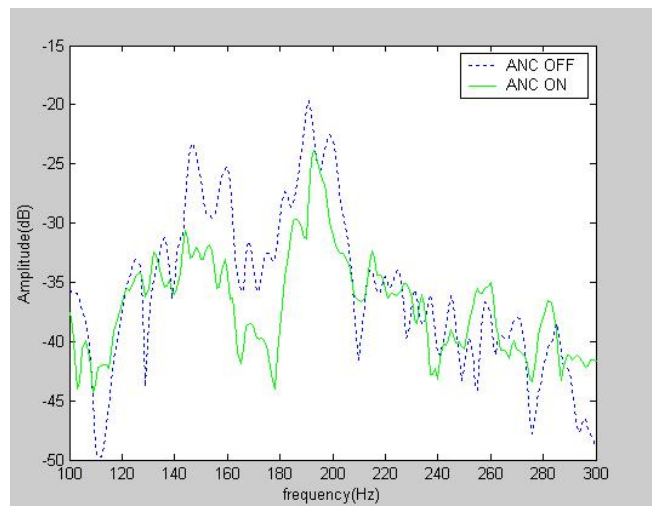

Fig. 4 Spectra of snore picked up by the microphone inside the left ear of KEMAR before and after ANC

A. Virtual Sensing Techniques

As shown in Figs. 3 and 4, the optimum locations of error microphones in snore ANC system are close to the listener's ears for maximum noise reduction because the "quiet zones" are centered at the error microphones. Therefore, the challenge is to create quiet zones at the locations of virtual sensors (i.e., ears of the bed partner) by placing physical error sensors on the headboard as shown in Fig. 2.

1) Class 1 - requiring preliminary identification

This class of algorithms [18, 19] requires system models or transfer functions to process the data obtained from physical sensors. During the training stage, sensors are deployed at the physical locations permanently and virtual locations temporarily. The sensing data is used to derive the transfer functions needed for virtual sensing methods. After the training stage, the sensors at the virtual locations are removed.

The system performance of this class of algorithms depends heavily on the accuracy of system models obtained during the off-line training stage, and is very sensitive to the locations of the physical sensors. In addition, it may need to repeat the off-line training process for the changing environment during the operation of ANC. Another limitation is that the off-line training is inapplicable (or difficult to realize) in some real-world applications.

2) Class 2-not requiring offline identification

The second class of algorithms does not need the off-line training stage. For example, Moreau [20] developed the stochastically optimal tonal diffuse field virtual sensing method for a spatially-fixed target zone, and extended it to moving targets. A contribution of this method is that it doesn't require off-line training stage to obtain system models (or transfer functions), thus it can be more efficiently and effectively applied to practical systems.

In many practical ANC applications, especially in consumer electronics and medical instruments, it is desired to shift quiet zone(s) away from the locations of the physical error sensors to the desired virtual locations for optimum performance. Therefore, development of effective virtual sensing techniques for ANC systems is a very important and challenging work, and it deserves further research and development.

B. RESIDUAL NOISE MASKING

ANC systems do not completely reduce primary noise due to many physical limitations. In some applications, the residual noise can be masked using suitable masking signals such as music or nature sounds.   Properly selected audio sound can create a very soothing atmosphere to help a person relax and sleep. This is one of the key reasons in exploring the use of audio for masking residual noise in snore ANC systems. In addition, the same audio can be used as a training signal for off-line secondary-path modeling, and extended to form an on-line secondary-path modeling technique. The use of audio is explored in the following areas:
1) Residual noise masking with soothing audio using principles of psychoacoustics.
2) Off-line modeling of secondary paths.

3) On-line secondary-path modeling for the FXLMS algorithm to update ANC filter.

A psychoacoustic processor is designed and integrated with the ANC systems to mask the residual snore noise at a volume as low as possible [21]. This system involves playing modified audio simultaneously with anti-noise to mask the residual noise. Figure 5 shows the integrated audio/ANC system performing both audio interference cancellation and on-line modeling of $S(z)$ [22]. The comfort audio $w_a(n)$ is added with the canceling signal $y(n)$ and the mixed signal $u(n)$ is output to drive the secondary loudspeaker. Thus, the signal $e(n)$ picked up by the error microphone contains both the true error signal and the desired audio component. The audio component is subtracted to obtain the true error signal $e'(n)$ to update the adaptive filter $W(z)$.

For consumer devices like snore ANC systems, it is preferred to use an enjoyable piece of music or audio as the lossless training signal in modeling performance. This motivates the use of nature sounds like raining, running streams, etc. for modeling the secondary paths.
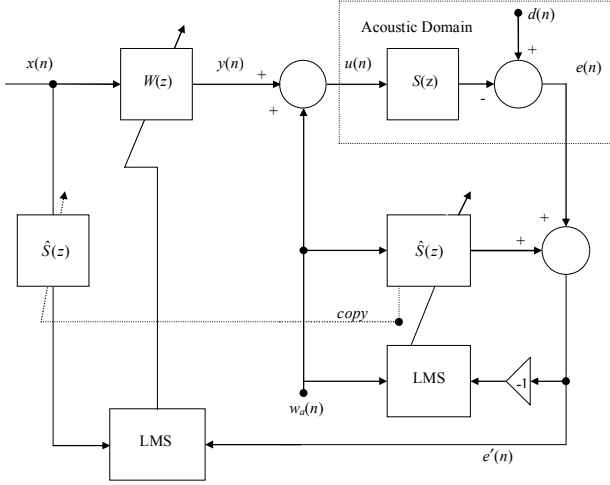

Fig. 5 Integrated audio/ANC system that provides both audio cancellation and on-line secondary-path modeling

In order to mask the residual noise seamlessly, the audio signal $w_a(n)$ must be chosen and processed by the psychoacoustic processor based on the characteristics of the residual noise. In addition, it is necessary to control the volume of the audio signal such that it matches the level of true residual noise. Therefore, more research is needed on psychoacoustics and human perception of sounds.

C. ACTIVE SOUND QUALITY CONTROL

In some applications, it is desirable to retain a low-level residual noise with a desired spectral shape or changed noise signature. Active sound quality control (ASQC), which changes amplitudes of noise components with predetermined values, is a useful and important extension of ANC. The system for individually controlling each harmonic of a periodic noise is called the narrowband active noise equalization [23]. The narrowband ASQC algorithm can be implemented and analyzed in frequency domain [24], and extended to control broadband noises [25]. The block diagram of the broadband ASQC system is illustrated in Fig. 6. The broadband ASQC algorithm uses a shaping filter $C(z)$ to control the residual noise spectrum. The filter is designed such that $|C(z)|^2$ is the desired shape of the residual noise spectrum.
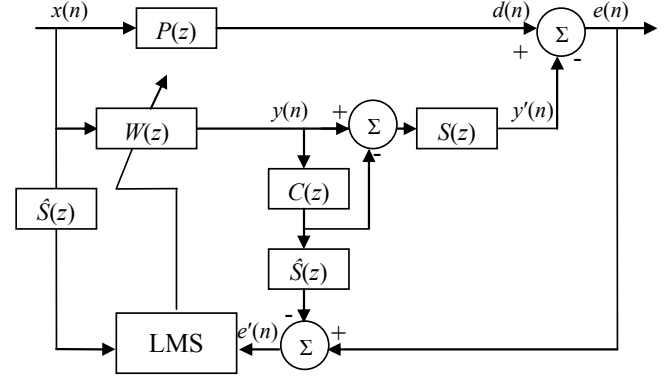

Fig. 6 Block diagram of the broadband ASQC system

Active sound quality control inherits the problems of ANC systems. These problems include passband disturbance due to the uncorrelated interference at frequencies of the magnitude response of secondary path with high gains, and slow convergence due to the eigenvalue spread of the input autocorrelation matrix determined by the secondary path. Further research is needed to design shaping filter $C(z)$, to analyze transient behaviors of the algorithm, and the modeling error of secondary-path estimates on the performance of system.

D. Some Special Noises

Active noise control systems are mainly developed for reducing low-frequency noises and stationary noises generated by engines, compressors, fans, and etc. This section introduces some challenging cases.

1) High Frequency Noises

Many new developments of ANC applications in consumer electronics and medical instruments involve reducing high-frequency noises in three-dimensional space. The first example is the development of privacy-phone handsets that picks up near-end speech, transmits it, and at the same time generates the out-of-phase speech to cancel the original speech in space, thus allowing private and quiet voice communication in public areas. Another potential application is the development of ANC systems for dental drills, where the frequency range of the dominant noise varies from 2000 to 6000 Hz for most of drills, depending on the rotation speed of the bearing [26].

Combination of both active and passive noise control techniques in small spaces such as headsets is the current solution for reducing noise with high and wide frequency range. With advances in acoustic theory and

control techniques, innovative ANC systems can be extended to higher frequencies.

2) Impulse-Like Noises

There are many practical ANC applications involve impulse-like noises. For example, soldiers need ANC helmets or headphones for protection against extremely high-level impulse-like noises from bomb explosions, gun shots, and etc. The real challenge is that the ANC headphones must selectively cancel harmful noises only, while still pass spatial and environmental information to the user. As for the second example, there are many loud impulse-like noises generated by stamping machines in industrial manufacturing plants.

Fig. 6 ANC setup based on the GE Giraffe® incubator

In hospitals, there are a lot of life-saving equipment such as breathing and IV pumps that generate impulse-like noises. For example, infant incubators shown in Fig. 6 are used in neonatal intensive care units (NICU) to increase the survival of premature and ill infants. The application of ANC for reducing incubator noise in NICU was developed in [27]. The recorded NICU noise has lot of warning sounds and IV pump sounds, which are impulse-like noises. The development of the nonlinear filtered-X least mean M-estimate algorithm for reducing impulse-like noise in incubators was reported in [27]. Further performance analysis, real-time experiments, and development of more effective ANC algorithms for impulse-like noises is needed.

3) Dynamic Active Noise Control

In recent years, traffic noise coming from streets, highways, railways, and airports has been of increasing concern. There is some research on improving the performance of noise barriers by using ANC systems, but the noise sources in these studies are assumed to be fixed. In practice, the positions of noise sources in real-world transportation applications are time varying, and it is necessary to study and develop dynamic ANC systems for moving noise sources relative to the ANC installation.

Little research has been done in active control of noise from moving sources [28, 29]. These publications show that the optimal noise controller for moving noise sources will vary when the positions of the primary noise sources change. However, the relationships among the noise reduction performance of ANC systems, the changed system transfer functions caused by the speed and direction of the moving sources, and the corresponding frequency shifting due to the Doppler effect have not yet been investigated. Therefore, there is need to research these three critical issues: (1) Time-varying primary paths, (2) the Doppler effects, and (3) large-scale and fast-convergence control algorithms.

IV. ADD-ON FUNCTIONS

One of the reasons for slow adoption of ANC is due to the higher initial cost as compared with available passive methods. To overcome this economic factor, some ANC systems can be more cost effective and attractive by adding additional functions on the products without increasing the overall system cost. This goal can be achieved by sharing the hardware resources such as amplifiers, loudspeakers, microphones, and etc.

The first example is the integrated audio/ANC system for infant incubators as shown in Fig. 6. It should be noted that the womb has a rich sound environment with sound mainly coming from the heart and blood vessels of the mother [30]. These sounds help the infant's neurological development and improve their understanding of rhythm and melody. Therefore, it is strongly desired to decrease the NICU noise and at the same time provide the infant with the ambience of the mother's womb. An audio-integration algorithm [29] introduces a healthy intrauterine sound with the ANC system to soothe the infants. The integrated system uses the same power amplifier and the loudspeakers inside the incubator (see Fig. 6), thus the overall system cost remains the same.

The second example of an add-on function is to use the microphones inside the incubator to detect and recognize the infant cry in order to alert and inform the nurse or caretaker of the most likely reason behind the cry [31]. This algorithm utilizes signal boundary detection and linear predictive coding (LPC) coefficients in order to analyze and extract features from infant cry instances. Consistent reference signals for three separate cry pathologies (hunger, wet diaper, and a need for attention) were decomposed to generate training vectors for cry recognition. Qualitative matching was defined on the basis of similarity between unknown cry LPC coefficients to the weighted coefficients of each of the three training vectors. Figure 7 shows that different cry signals have varying LPC coefficients. This suggests that LPC can be used to differentiate cries. Further research is needed to evaluate different features and sound recognitions techniques.

Another example of add-on functions to ANC systems is to integrate audio entertainment and hands-free phone communications features into the snore ANC system as shown in Fig. 3. In this case, the loudspeakers on the headboard and the associated amplifiers are available for audio entertainment purpose. In addition, with the microphones on the headboard along with the loudspeakers and associated amplifiers, a hands-free speakerphone can be developed as an add-on feature to the snore ANC system.

This additional feature involves the development of acoustic echo cancellation techniques.
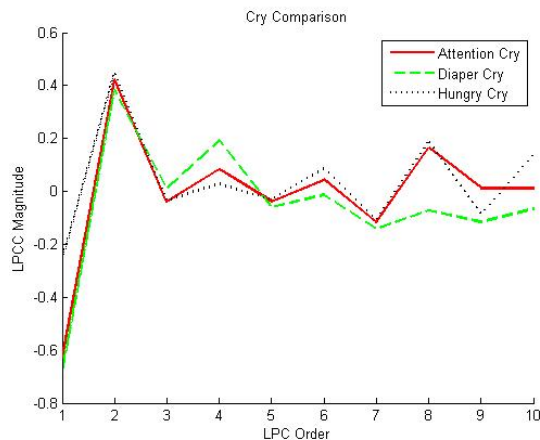

Fig. 7 LPC coefficient sets of attention, diaper and

hungry cries

V. CONCLUSIONS

This paper presented open problems and challenges of ANC systems from the signal processing viewpoint. Several open research and development problems were given. Three important techniques: virtual sensing, residual noise masking, and active sound quality control, were proposed to further improve performance of ANC systems. We also presented some potential but difficult ANC applications for high-frequency and impulse-like noises, and traffic noise with moving noise sources. Finally, we suggested add-on functions for designing more attractive and cost-effective ANC systems.

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