WIRELESS COMMUNICATION INTEGRATED ACTIVE NOISE CONTROL SYSTEM FOR INFANT INCUBATORS

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ABSTRACT

Every year, 20 million premature, low-birth-weight, very ill babies are born and most of them are saved by infant incubators. However, the high-level noise inside the incubator results in numerous adverse health effects. It is also difficult for parents bonding with their baby placed in an incubator inside neonatal intensive care unit (NICU). This paper presents a wireless communication integrated active noise control (ANC) systems for infant incubators. The system can generate safe, quiet environment for the newborn in the incubator and provide bonding opportunities for infant and their parents both inside and outside the NICU.

***Index Terms*—**Active noise control, infant incubator, bonding, wireless communication, integrated.

1. INTRODUCTION

Newborn babies in need of intensive medical attention are often admitted into the NICU, which combines advanced technology and trained healthcare professionals. Incubators have greatly increased the survival of very low birth weight and premature infants. However, high levels of noise in the NICU have been shown to result in numerous adverse health effects, including hearing loss, sleep disturbance and other forms of stress [1].

On the other hand, the most important relationship (bonding) in a child's life is the attachment to his or her primary caregiver. This is due to the fact that this first relationship determines the biological and emotional 'template' for all future relationships. Healthy attachment to the mother built by repetitive bonding experiences during infancy provides the solid foundation for future healthy relationships [2].

However, infants admitted to NICU may loss such experiences in their earliest life due to the limited access to NICU for their parents. Therefore, it is extremely important to reduce noise level inside incubator and increase bonding opportunities for NICU babies and their parents. In addition, they are advantages for newborns inside the incubators to hear their mothers' voice which can help release the stress and improve language development. Communicating with NICU babies can also benefit the new mothers, such as, preventing postpartum depression, improving bonding, etc [3].

In this paper, we propose wireless communication integrated ANC system that combines the wireless communication system and ANC algorithms for incubator. ANC is able to cancel unwanted noises and the wireless communication part can provide two way communications between parents and infants.

Figure 1 shows the block diagram of the proposed integrated ANC system. It includes two parts: (1) the ANC part is developed to reduce the external harmful noise for the infant incubator; (2) wireless communication system integrated with ANC system to provide communication between infants and their parents or caregivers. In order to comfort infants, the desired speech signal, such as, mother's voice is picked up, processed and played to infant through the anti-noise loudspeaker inside the incubator. The infant audio signals such as crying, breathing, and cooing, will be picked up by the error microphone inside the incubator, processed, and played to his/her parents wirelessly.

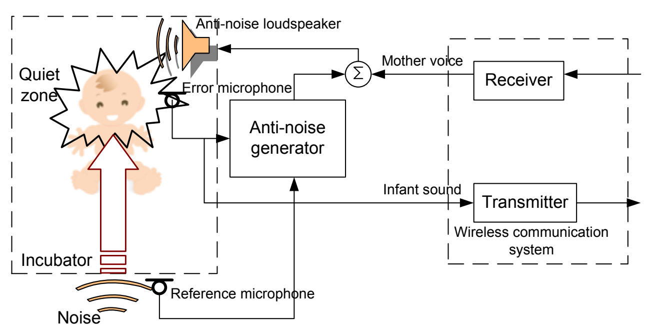

Fig. 1 Block diagram of wireless communicating integrated multi-channel ANC system

2. MULTI-CHANNEL ANC SYSTEM

For a general multi-channel ANC system, as shown in Fig. 2, we assume there are J reference sensors, K secondary sources and M error sensors. The J channels reference signals can be expressed as: $\mathbf{x}(n) = \left[\mathbf{x}_1^T(n) \quad \mathbf{x}_2^T(n) \quad \cdots \quad \mathbf{x}_J^T(n)\right]^T$ with $\mathbf{x}_j(n)$ is the jth-channel reference signal of length L. The secondary sources have K channels, $\mathbf{y}(n)=\left[y_1(n) \quad y_2(n) \quad \cdots \quad y_K(n)\right]^T$, where $y_k(n)$ is the signal of kth output channel at time n. The error signals have M channels, $\mathbf{e}(n)=\left[e_1(n) \quad e_2(n) \quad \cdots \quad e_M(n)\right]^T$ where $e_m(n)$ is the error signal of mth error channel at time n. Both the primary noise $\mathbf{d}(n)$ and the cancelling noise $\mathbf{d}'(n)$ are vectors with M elements at the locations of M error sensors [4].

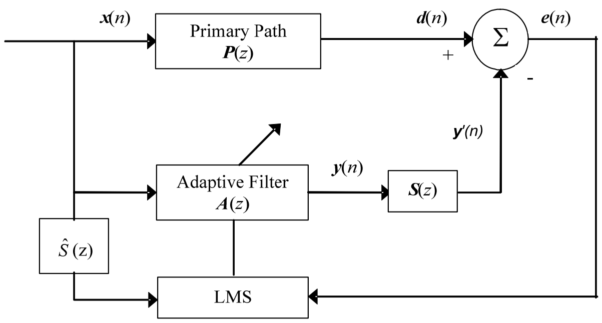

Fig. 2 Block diagram of multi-channel ANC system

The primary paths impulse responses can be expressed by a matrix as

$$\mathbf{P}(n)=\begin{bmatrix} p_{11}(n) & p_{12}(n) & \cdots & p_{1J}(n) \\ p_{21}(n) & p_{22}(n) & \cdots & p_{2J}(n) \\ \vdots & \vdots & \ddots & \vdots \\ p_{M1}(n) & p_{M1}(n) & \vdots & p_{MJ}(n) \end{bmatrix}$$

where $p_{mj}(n)$ is the impulse response function from the jth reference sensor to the mth error sensor. The matrix of secondary path impulse response functions is given by

$$\mathbf{S}(n)=\begin{bmatrix} s_{11}(n) & s_{12}(n) & \cdots & s_{1K}(n) \\ s_{21}(n) & s_{22}(n) & \cdots & s_{2K}(n) \\ \vdots & \vdots & \ddots & \vdots \\ s_{M1}(n) & s_{M2}(n) & \cdots & s_{MK}(n) \end{bmatrix}$$

where $s_{mk}(n)$ is the impulse response function from the kth secondary source to the mth error sensor. An estimate of **S**(n), denoted as $\hat{\mathbf{S}}(n)$, can be similarly defined.

Matrix $\mathbf{A}(n)$ consists of feedforward adaptive finite impulse response (FIR) filters impulse response functions, which has J inputs, K outputs, and filter order L, $\mathbf{A}(n)=\left[\mathbf{A}_1^T(n) \quad \mathbf{A}_2^T(n) \quad \cdots \quad \mathbf{A}_K^T(n)\right]^T$, where $\mathbf{A}_k(n)=\left[\mathbf{A}_{k,1}^T(n) \quad \mathbf{A}_{k,2}^T(n) \quad \cdots \quad \mathbf{A}_{k,J}^T(n)\right]^T$, *k=1,2,…,K* is the weight vector of the kth feedforward FIR adaptive filter with J input signals defined as $\mathbf{A}_{k,j}(n)=\left[a_{k,j,1}(n) \quad a_{k,j,2}(n) \quad \cdots \quad a_{k,j,L}(n)\right]^T$, which is the feedfroward FIR weight vector form jth input to kth output.

The secondary sources are driven by the summation of the feedforward and feedback filters outputs. That is

$$y_k(n)=\sum_{j=1}^{J}\mathbf{x}_j^T(n)\mathbf{A}_{k,j}(n)=\mathbf{x}^T(n)\mathbf{A}_k(n) \tag{1}$$

The error signal vector measured by M sensors is

$$\begin{aligned}\mathbf{e}(n)&=\mathbf{d}(n)+\mathbf{y}'(n)\\ &=\mathbf{d}(n)+\mathbf{S}(n)*\left[\mathbf{X}^T(n)\mathbf{A}(n)\right]\end{aligned} \tag{2}$$

where $\mathbf{d}(n)$ is the primary noise vector and $\mathbf{y}'(n)$ is the canceling signal vector at the error sensors.

The filter coefficients are iteratively updated to minimize a defined criterion. We use the sum of the mean square errors as the cost function defined as

$$\xi(n)=\sum_{m=1}^{M}E\left\{e_m^2(n)\right\}=\mathbf{e}^T(n)\mathbf{e}(n) \tag{3}$$

The least mean square (LMS) adaptive algorithm uses a steepest descent approach to adjust the coefficients of the feedfoward and feedback adaptive FIR filters in order to minimize $\xi(n)$ as follows [5]:

$$\mathbf{A}(n+1)=\mathbf{A}(n)-\mu_a\mathbf{X}'(n)\mathbf{e}(n) \tag{4}$$

where μ_a and μ_b are the step sizes for feedforward and feedback ANC systems, respectively. In real-time experiments, we use different values to improve convergence speed.

$$\mathbf{X}'(n)=\left[\mathbf{S}(n)*\mathbf{X}^T(n)\right]^T$$

$$=\left[\begin{bmatrix} \hat{s}_{11}(n) & \hat{s}_{12}(n) & \cdots & \hat{s}_{1K}(n) \\ \hat{s}_{21}(n) & \hat{s}_{22}(n) & \cdots & \hat{s}_{2K}(n) \\ \vdots & \vdots & \ddots & \vdots \\ \hat{s}_{M1}(n) & \hat{s}_{M2}(n) & \cdots & \hat{s}_{MK}(n) \end{bmatrix} * \begin{bmatrix} \mathbf{x}(n) & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{x}(n) & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{x}(n) \end{bmatrix}^T\right]^T$$

$$=\begin{bmatrix} \mathbf{x}'_{11}(n) & \mathbf{x}'_{12}(n) & \cdots & \mathbf{x}'_{1M}(n) \\ \mathbf{x}'_{21}(n) & \mathbf{x}'_{22}(n) & \cdots & \mathbf{x}'_{2M}(n) \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{x}'_{K1}(n) & \mathbf{x}'_{K2}(n) & \cdots & \mathbf{x}'_{KM}(n) \end{bmatrix}$$

that is

$$\begin{aligned}\mathbf{x}'_{km}(n)&=s_{mk(n)}*\mathbf{x}(n)\\ &=\left[s_{mk(n)}*\mathbf{x}_1^T(n) \quad s_{mk(n)}*\mathbf{x}_2^T(n) \quad \cdots \quad s_{mk(n)}*\mathbf{x}_J^T(n)\right]\\ &=\left[\mathbf{x}'^T_{km1}(n) \quad \mathbf{x}'^T_{km2}(n) \quad \cdots \quad \mathbf{x}'^T_{kmJ}(n)\right]\end{aligned}$$

The updated adaptive filter's coefficients can be expressed,

$$\mathbf{A}_k(n+1)=\mathbf{A}_k(n)-\mu\sum_{m=1}^{M}\mathbf{x}'_{km}(n)e_m(n) \tag{5}$$

and it can be further expended as

$$\begin{aligned}\mathbf{A}_{k,j}(n+1) &= \mathbf{A}_{k,j}(n) - \mu\sum_{m=1}^{M}\mathbf{x}'_{km}(n)e_m(n) \\ &= \mathbf{A}_{k,j}(n) - \mu\sum_{m=1}^{M}[s_{mk}(n) * \mathbf{x}_j(n)]e_m(n)\end{aligned} \tag{6}$$

3. WIRELESS COMMUNICATION SYSTEM

In this session, we introduce the wireless communication system to provide two-way communication between NICU residences and their parents or guardians inside and outside of NICU. In order to comfort infants, the desired audio signal, such as, mother's voice is picked up, processed, and played to infant through the anti-noise loudspeaker inside the incubator. The infant audio signals such as crying, breathing, and cooing, will be picked up by the error microphone inside the incubator, processed, transmitted wirelessly, and played to his/her parents. This developed system allows parents outside the NICU to talk to and listen from the infant inside the incubator, thus improves bonding for parents without visiting NICU with limited time periods.

We propose to use DS/SS technique to conduct wireless communication. The other techniques, such as, OFDM or UWB will be investigated in our future research. In DS/SS communications, each information symbol is spread using a length-L spreading code. That is,

$$d(k) = v(n)c(n,l) \tag{7}$$

where $v(n)$ is the symbol-rate information bearing voice signal, $c(n, l)$ is the binary spreading sequence of the nth symbol. We use $c(n)$ instead of $c(n, l)$ for simplicity.

The received chip rate matched filtered and sampled data sequence can be expressed as the product of the chip-rate sequence $d(k)$ and its spatial signature h,

$$p(k) = d(k)h \tag{8}$$

Within a symbol interval, after chip-rate processing received
data becomes

$$\mathbf{r} = \mathbf{p} + \mathbf{w} \tag{9}$$

where the L by 1 vector $\mathbf{p}$ contains signal of interest; $\mathbf{w}$ is the white noise.

4. WIRELESS COMMUNICATION INTEGRATED ANC SYSTEM

In this session, we introduce the wireless communication integrated ANC system for infant incubators. In addition to reducing harmful noise stimuli, the integrated ANC algorithm provides bonding opportunities between infants and their parents or caregivers wirelessly.

The voice signal $v(n)$ is added to the adaptive filter output $y(n)$, then the mixed signal propagates through the secondary path $S(z)$ to generate anti-noise $y'(n)$. At the quiet zone, the primary noise $d(n)$ is canceled by the anti-noise, resulting in the error signal $e_v(n)$ sensed by the error microphone, which contains the residual noise and the audio signal. To avoid the interference of the audio on the performance of ANC, the audio signal $v(n)$ is filtered through the secondary-path estimate $\hat{S}(z)$ and subtracted from $e_v(n)$ to get the true error signal $e(n)$ for updating the adaptive filter $A(z)$.

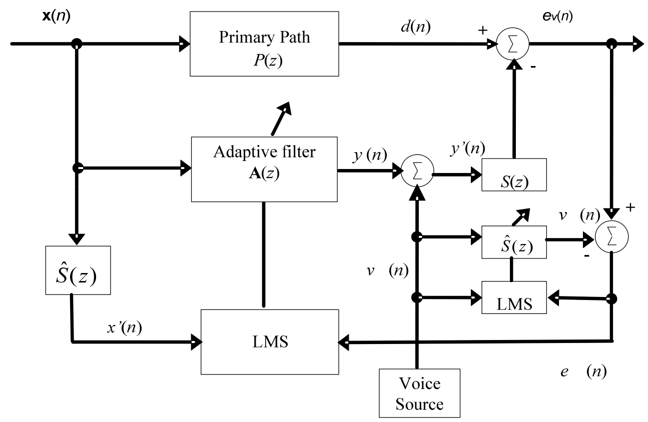

Fig. 3 Block diagram of audio integrated multi-channel ANC system

Using the z-domain notations [7], $Ev(z)$ can be expressed as

$$Ev(z) = D(z) - S(z)[Y(z) + V(z)], \tag{10}$$

The actual error signal $E(z)$ is expressed as

$$\begin{aligned}E(z) &= Ev(z) + \hat{S}(z)V(z) \\ &= D(z) - S(z)[Y(z) + V(z)] + \hat{S}(z)V(z).\end{aligned} \tag{11}$$

Assuming that the perfect secondary-path model is available, i.e., $\hat{S}(z) = S(z)$, we have

$$E(z) = D(z) - S(z)Y(z)\,. \tag{12}$$

This shows that the true error signal is obtained in the integrated ANC system, where the voice signal is removed from the signal $e_v(n)$ picked up by the error microphone. Therefore, the audio components won't degrade the performance of the noise control filter $A(z)$.

The advantages of the integrated ANC system are summarized as follows: 1) It provides audio comfort signal from the wireless communication devices, 2) it masks residual noise after noise cancellation, 3) it eliminates the interference of audio on the performance of ANC system, and 4) it integrates with the existing ANC's audio hardware such as amplifiers and loudspeakers for saving overall system cost.

5. SIMULATION RESULTS

The multiple-channel ANC system shown in Fig. 3 with J=1, K=2 and M=2 is evaluated when the primary noise is recorded incubator noise. The spectra of error signals before and after ANC at the left and right error microphones are shown in Fig. 4. Clearly, there is satisfactory reduction of the recorded incubator noises over the entire frequency range of interest. Average noise cancellation is 30 dB at the left error microphone, and 35 dB at the right error microphone.

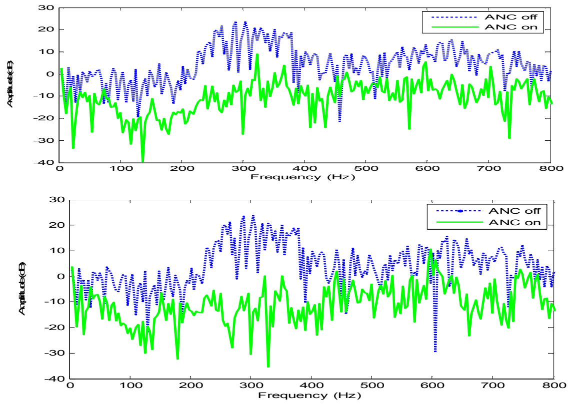

Fig. 4 Spectra of the error signals at the left (upper) and right (lower) error microphone before and after the multiple-channel ANC system

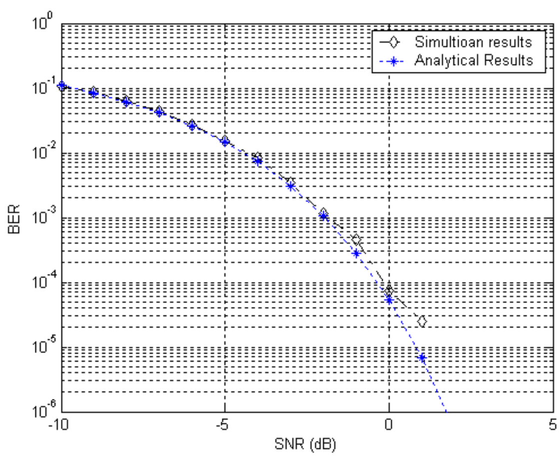

Fig. 5 BER vs. SNR of the proposed DS/SS wireless communication system

For wireless communication system simulation, only single user is considered with Rayleigh channel and the DS/SS signal uses Gold code of length L=15. Fig. 5 shows the BER vs. SNR results. The simulation result shows a good match with the analytical result.

The recorded female speech file was used to evaluate the performance of the integrated ANC system. The spectrogram for speech with noise (ANC OFF), speech only, speech with ANC ON is shown in Fig. 6. The observations of the results are summarized as follows: 1) Average noise reduction is around 30 dB. 2) Addition of speech signals didn't degrade the performance of the ANC system. 3) The added speech components are not cancelled by the ANC system, thus preserving the quality of the speech

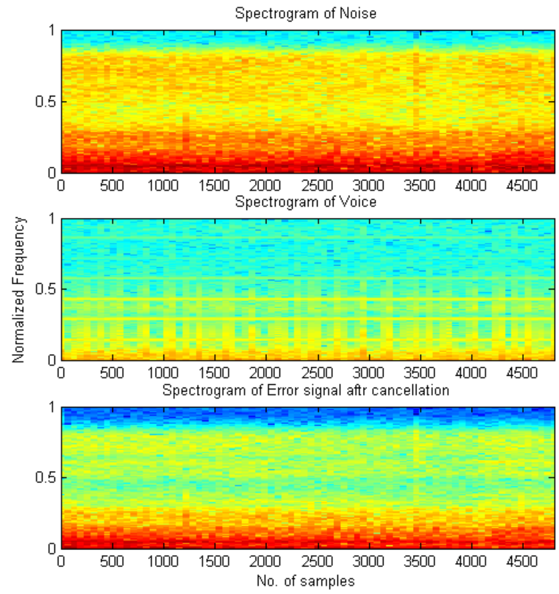

Fig. 6 Spectrogram of the noise signal, voice signal and error signal after cancellation

6. CONCLUSIONS

This paper introduced wireless communication integrated ANC system to cancel noises for infant incubators while provide bonding opportunities for the patients and their parents. The wireless communication integrated multi-channel ANC was presented and verified by computer simulations. Our future research includes: the feasibility of other wireless communication techniques for infant incubators, the effects of infant cry to the ANC system and the effects of ANC system to infant cry signals.

7. REFERENCES

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