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Multi-channel Real Time Active Noise Control System for Infant Incubators

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Abstract—**Excessive noise levels inside infants incubators in neonatal intensive care units (NICU) contribute to number of harmful effects on the infant's health. This paper develops and implements practical active noise control (ANC) systems for the infant incubators. The filtered-X least mean square (FXLMS) algorithm is used to cancel the noise inside the incubator. The multi-channel and pseudo multi-channel ANC systems are proposed to enhance the noise cancellation performance in terms of cancellation gain and quiet zone. An experimental setup based on real Giraffe incubator from GE Healthcare is used for real-time experiments. The results show that the ANC system can dramatically reduce the noise and cost effective.**

I. Introduction

Premature infants or preemies with organs not fully developed begin their first period life enclosed in infant incubators in NICUs, where they are cared for till they are considered fully developed. There are a lot of noises generated by medical instruments inside the NICU. Those noises may affect infants's health, for example, noises result in infants' hearing and cause communication disorder of language development disorder in the future [1]. The noise inside NICU may cause cochlear damage and disrupt the normal development of the infant [2]. Intense noises can cause serious psychological responses in infants such as changes in heart rate, blood pressure, oxygenation, respiration, intestinal peristalsis, and glucose consumption [3]. Loud noises in NICU considerably changed the behavioral and psychological responses of infants [2]. On the basis of these studies, adverse noise-induced health effects on infants are diverse in nature.

To reduce the noise level, passive techniques such as using absorbers [4-6] were not effective. Passive techniques can effectively attenuate only high-frequency noise, and their performance at lower frequencies is limited. This heightens the need for an ANC system to reduce the noise inside the incubators. ANC works based on the principle of superposition, i.e., an anti-noise with equal amplitude and opposite phase is generated by the system and combined with the primary noise to cancel the undesired noise. Therefore, the low frequency noise also can be decreased.

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In [7], the single channel ANC system is presented to control the noise in the incubator. However, the noise cancellation gain and the quiet zone is not good enough according our real time experiment. Therefore, in this paper the multi channel ANC system is developed based on the single channel one. Although it achieves much better performance, the hardware and software cost also dramatically increases. To reduce the cost and provide reasonable performance as well, we also propose to use the pseudo multi channel ANC system. The real time experiment shows that the new system can provide good noise cancellation performance in the incubator and cost effective.

In Section 2, the single channel ANC system is introduced. Section 3 presents the multi channel and pseudo multi channel ANC systems. Section 4 shows the experiment setup and the experimental results. Section 5 summarizes the conclusion.

II. The Brief Introduction for Single channel ANC System

In this section, we briefly introduce the single channel ANC system; the interested readers can find more details in [7]. The feedforward ANC systems with reference microphone are required to cancel broadband incubator noise. A single-channel ANC system uses one reference microphone, one secondary loudspeaker, and one error microphone. The primary noise from unknown noise sources is picked up by the reference microphone, processed by the ANC system to generate the anti-noise, which is sent to the secondary source (loudspeaker) for canceling the undesired noise. The error microphone monitors the performance of ANC system by measuring the residual noise, which is used for updating coefficients of the adaptive filter.

The signal-flow diagram of single-channel ANC system is shown in Fig. 1 [8]. The transfer function $P(z)$ is the primary path between the noise source and the error microphone. The adaptive filter $W(z)$ using the reference signal $x(n)$ and the least-mean-square (LMS) algorithm to update its coefficients in order to track the changes of physical plants. The filter output $y(n)$ is send to the secondary loudspeaker to produce anti-noise $y'(n)$, which is acoustically superimposed with the primary noise $d(n)$ to minimize the error signal (residual noise) $e(n)$.

In Fig. 1, $S(z)$ represents the secondary path from the secondary loudspeaker to the error microphone. The filtered-x LMS (FXLMS) algorithm compensates the effect of secondary path by placing the secondary-path model $\hat{S}(z)$ in the signal path before the weight update of the LMS algorithm [9]. In practical applications, the secondary path $S(z)$ is unknown and it must be estimated by the adaptive filter $\hat{S}(z)$ using the off-line modeling technique [8], also called offline training. This preliminary identification needs to be repeated if the environment changes.

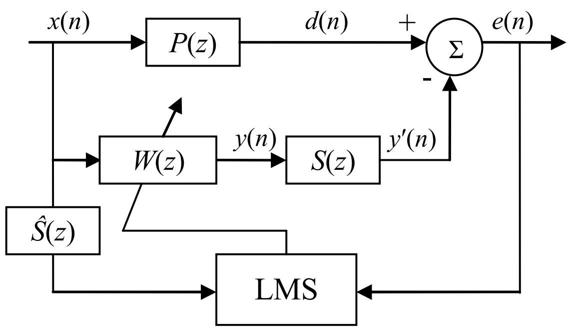


Fig. 1 The single channel feedforward ANC system

Real-time experiments of the single-channel ANC system are conducted in Section IV to evaluate the effectiveness of the algorithm for noise reduction. The experimental results show single-channel ANC system is not able to provide satisfactory performance, for example, the quiet zone is relatively small and the cancellation gain is not sufficient. Thus multi-channel ANC systems are required to create a larger size of quiet zone with higher noise reduction.

III. Multi Channel and Pseudo Multi Channel ANC Systems

A. Multi Chanel ANC System

In order to improve the performance of the single channel ANC system, let us first consider a 1x2x2 multi-channel active noise system as shown in Fig. 2. One reference microphone is used to pick up the primary noise, two error microphones senses the residual noise and two loudspeakers generate 'anti noise'. The primary path transfer functions $P(z), i=1,2$ are from the noise source to both the error sensors. The primary noises to be cancelled are $d_1(n)$ and $d_2(n)$. The residual noise $e_i(n)$ is picked up by the ith error sensor. The secondary path transfer functions $S_{ij}(z), i=1,2$ and $j=1,2$ are from $y_j(n)$ to the error signals $e_i(n)$. The canceling signals $y_j(n)$generated by the adaptive filters $W_j(z)$ with $j=1,2$. The residual noises are given by:

$$e_i(n) = d_i(n) - \sum_{j=1}^{2} y_j(n) s_{ij}(n), \quad i = 1,2 \qquad [1]$$

$$d_i = p_i(n) * x(n), \quad i = 1,2 \qquad [2]$$

where $s_{ij}(n)$and $p_i(n)$ are impulse responses of the secondary paths and primary paths respectively. The adaptive filters outputs are:

$$y_i(n) = \mathbf{w}_i^T(n)\mathbf{x}(n), \quad i = 1,2 \qquad [3]$$

where the adaptive filter coefficient vectors are $\mathbf{w}_i(n) = \left[w_{i0}(n) \quad w_{i1}(n) \quad \text{L} \quad w_{iL}(n) \right]^T$, the input vector is $\mathbf{x}(n) = \left[x(n) \quad x(n-1) \quad \text{L} \quad x(n-L+1) \right]^T$ and L is the filter order. The weight update equations are:

$$\mathbf{w}_i(n+1) = \mathbf{w}_i(n) + \mu \sum_{j=1}^{2} e_i(n)\mathbf{x}(n) * \hat{s}_{ij}(n), \quad i = 1,2. \qquad [4]$$

where μ is the step size, $\hat{s}_{ij}(n)$ are estimations of $s_{ij}(n)$ and we use LMS algorithm and white noise to estimate the secondary paths.

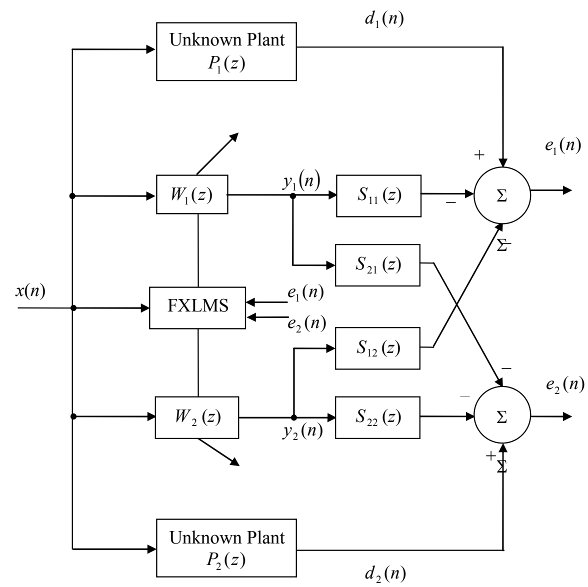


Fig. 2 The 1x2x2 multichannel feedforward ANC system

B. Pseudo Multi- Chanel ANC System

Compared with the single-channel ANC system, the 1x2x2 FXLMS algorithm needs two adaptive filters instead of one, and requires four secondary-path models instead of one. In addition, the two-channel ANC system needs two input channels to obtain error signals $e_1(n)$ and $e_2(n)$ instead of one to obtain $e(n)$, where each input channel consists of a preamplifier, an anti-aliasing lowpass filter, and an analog-to-digital converter. Also, the two-channel ANC system needs two output channels instead of one, where each output channel consists of a digital-to-analog converter, a reconstruction lowpass filter, and a power amplifier. These analog devices are usually expensive for using high-quality components. Therefore the cost of this 1x2x2 multichannel ANC system is about double of the single channel system.

To achieve better performance than the single-channel ANC system but require lower system cost than the 1x2x2 FXLMS algorithm, the pseudo multi-channel ANC system is developed in this section. This simplified algorithm is based on the single-channel FXLMS algorithm and shown in Fig. 3, which only needs one error signal $e(n)$ and generates one output signal $y(n)$. However, after the digital output $y(n)$ is converted to analog signal, it is amplified to drive both loudspeakers used in the 1x2x2 ANC system. Also, two analog signals picked up by error microphones are mixed by an analog mixer to get an analog error signal, which is converted to $e(n)$. Therefore, the pseudo two-channel ANC system uses one reference microphone, two secondary loudspeakers, and two error microphones which is the same as the two-channel ANC system, however, it uses the single-channel FXLMS algorithm with only one input channel for sensing error signal and one output channel for generating canceling signal.

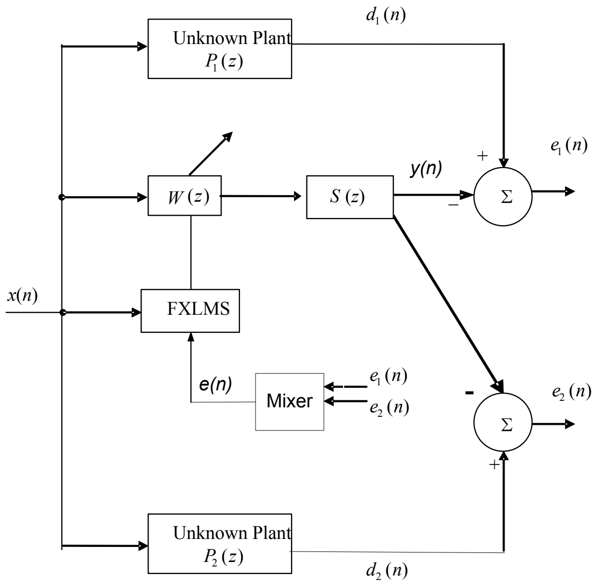
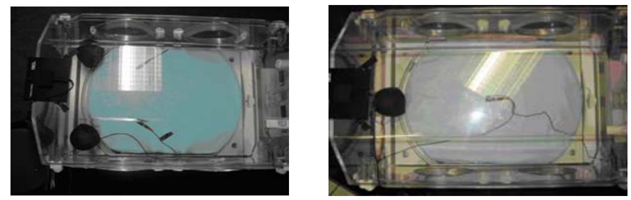


Fig. 3 The pseudo multichannel feedforward ANC system

IV. Real time Experiments Results

The performance of ANC systems is evaluated by real-time experiments using the Giraffe incubator from GE Healthcare. Fig. 4 shows the experimental setup for the single, two-channel and pseudo two-channel ANC systems. An independent loudspeaker at the outside of the incubator is used as a noise source that produces the primary noise. A reference microphone is placed on the top of the incubator to pick up the primary noise. For the single channel system, one second loudspeaker is used to generate the anti noise, and one error microphone is used to pick up the residue noise. In the pseudo multi or multi channel systems, two loudspeakers are placed at the two corners of the incubator to generate the anti-noise. Two error microphones (black) are placed on the mattress. For all these systems, two extra microphones are used to measure the noise levels inside the incubator at different locations when the ANC is turned on and off. As shown in Fig. 5, a 3D grid is built for global noise cancellation measurement purpose; each plane of the grid has (8X13=104) measuring points. The measuring microphone is first located at the location (1, 1) of z = 1 plane to obtain noise reduction at that point, then the microphone is moved to different locations on the bar along the x-y axis on the same z-plane to measure noise reduction at all 104 locations. The experiment is repeated for z = 2, 3, 4, and 5 planes and the noise reduction at all 520 measuring points are obtained and reported in [10].

The primary microphone has a switch to turn on and off of the ANC by gradually producing zero output and freezing the filter coefficients. The single-channel, multi-channel and pseudo multi-channel ANC algorithms are implemented on the floating-point digital signal processor, TMS320C30, for real-time experiments. The spectrum plots are obtained using a Hewlett-Packard spectrum analyzer (35670A) with the averaging function, and plotted by a MATLAB program.



(a) (b)

Fig.4. The real time experiment setups for ANC systems (a) multichannel and pseudo multichannel system (2) single channel system

A. Single Channel Results

In this experiment, a 200 Hz tone is used as the primary noise. The gains and locations of the error microphone and secondary loudspeaker are fixed; only the location of the measuring microphone is changed to different points on the 3-D grid (as shown in Fig 5) to record noise levels when the ANC is turned on and off. The difference between the original and residual noise levels is the net noise reduction at that location.

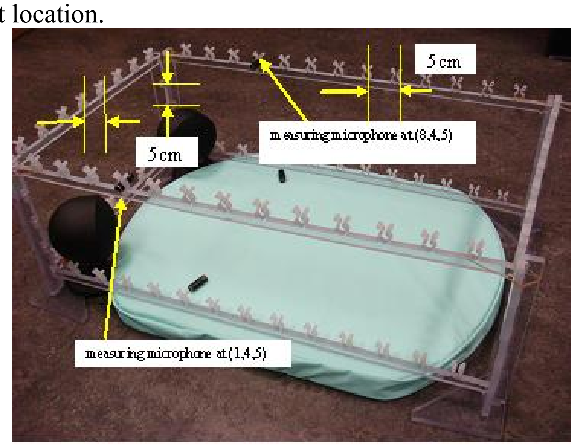


Fig. 5 The grid for measuring real-time ANC performance at uniformly-spaced (x,y,z) locations inside the incubator. For example, the two measuring microphones are placed at (1,4,5) and (8,4,5) positions.

Since the plane at z = 1 (5 cm above the mattress) is most close to the ears of infants, we only show the results when z=1 in Fig. 6. The noise reduction of 15-20 dB can be achieved at many points, and higher noise cancellation points are away from the loudspeaker. The single-channel ANC system shows good performance only at the locations close to the error microphone. At some measuring points close to the loudspeaker, there is increase in the noise levels indicated by negative numbers.

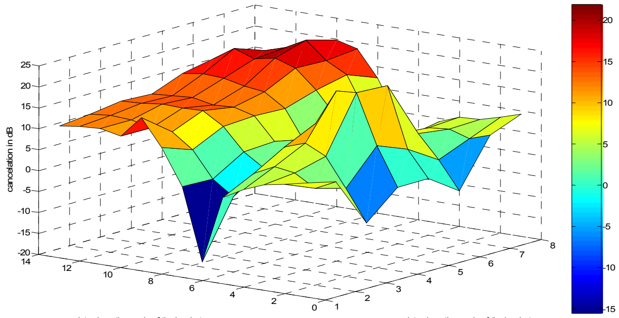


Fig 6. Single channel ANC system results

B. Multi and Pseudo Multi Channel Results

In order to compare with the single-channel ANC system, the next set of experiments using the same 200 Hz tone as the primary noise, and the amplifier gains and experiment steps are the same as the single-channel system presented in previous subsection to give a fair comparison. The noise reduction at all measuring points are reported in [10]. The net noise reduction on the z =1 plane is summarized and the corresponding 3-D plot is shown in Fig 7. The higher noise cancellation can be obtained at the locations of x = 9, 10, 11, 12, and 13. This is agreed with the single-channel ANC system that higher noise cancellation locations are away from the secondary loudspeakers. The noise reduction is in the range of 5-40 dB at all measuring points; and noise levels will not be increased at any location, which is a significant improvement over the single-channel ANC system.

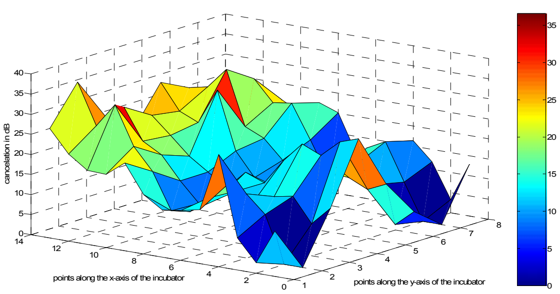


Fig 7. Multi Channel ANC system Results

To achieve better performance than the single-channel ANC system but require lower system cost than the 1x2x2 FXLMS algorithm, the pseudo multi-channel ANC system is developed in Section III. B.

The noise reduction at all the measurement points on the z = 1 plane are summarized Fig. 8. As compared to Fig 6, the pseudo multi-channel ANC system shows significant improvement over the single-channel ANC system. These two systems have the identical computational complexity and the same number of input-output channels; the only additional cost is the extra one microphone and one loudspeaker, which are relatively cheap because they are used by large numbers of consumer audio products. Comparing Fig. 7 with Fig. 8, the true multi-channel ANC system with the 1x2x2 FXLMS algorithm achieved better performance than the pseudo system, however, as discussed in Section III.B, the multi-channel ANC system requires higher system cost due to its computational complexity and required input-output channels.

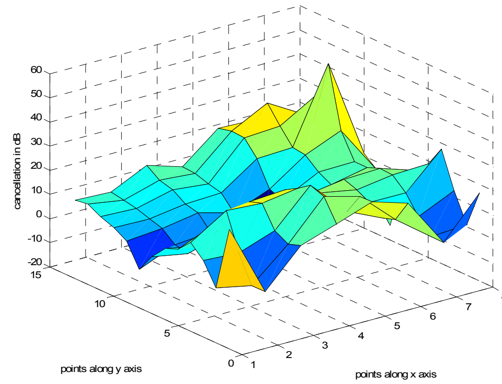


Fig. 8 Pseudo multi channel results

IV. CONCLUSION

This paper focused on developing practical ANC systems using the real incubator to reduce the high levels of noise associated with the incubator. The incubator noise was reduced using the practical ANC system. Multi-channel and pseudo-multi channel ANC systems are presented to enhance the global noise cancellation performance compared to the single channel system. The real time experiment results show that the pseudo multi channel system is easy to operate, cost-effective and with satisfactory performance.

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