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Active Noise Control for Infant Incubators

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Abstract— **This paper presents an active noise control system for infant incubators. Experimental results show that global noise reduction can be achieved for infant incubator ANC systems. An audio-integration algorithm is presented to introduce a healthy audio (intrauterine) sound with the ANC system to mask the residual noise and soothe the infant. Carbon nanotube based transparent thin film speaker is also introduced in this paper as the actuator for the ANC system to generate the destructive secondary sound, which can significantly save the congested incubator space and without blocking the view of doctors and nurses.**

I. Introduction

INFANT incubators are widely used in neonatal intensive care units (NICU) for the care of pre-term babies. The infant incubator is an enclosure designed to hold an infant with transparent sections for viewing, sensors and devices for monitoring vital statistics of the baby, and environmental control for temperature, humidity, supplementary gas and etc. Incubators are mainly utilized for pre-term babies (less than 37 weeks of gestation). Incubators and NICUs have greatly increased the survival of very-low-birth-weight and premature infants. Over the past 20 years, the survive rate of those infants (<1,500 grams) has increased by more than 80% [1]. However, high levels of noise inside the incubators have been found to result in numerous adverse health effects including hearing loss, sleep disturbances and other forms of stress, as well as alterations in physiological responses, such as heart and respiratory rate, blood pressure and oxygen saturation [2-6]. Three to five percent of extremely premature survivors are profoundly deaf [2, 3], while approximately 52% of infants with normal hearing who are placed in incubators exhibit changes in their audiograms that are consistent with minor acoustic trauma [4]. These adverse health effects will have lifelong consequences to the quality of life for NICU graduates.

Incubator noise is typically broadband (<1000 Hz) and is generated by equipments such as IV pumps, fans, warning sounds, and heating machinery. Currently, unfortunately, there are few developed methods that are effective for reducing incubator noise. Most attempts to improve the acoustic environment of the NICU have focused on reducing staff activity [7], and/or incorporating sound containment and absorption strategies into the design of new NICU [8, 9]. Those methods are ineffective for low-frequency NICU noises. It is therefore of importance to research new approaches that can significantly reduce noise levels inside incubators.

It should be noted that not all sounds are harmful to infants. The womb is not a silent place; it has a rich sound environment with sound mainly coming from the heart and blood vessels of the mom [10]. These sounds help the infants' neurological development and improve their understanding of rhythm and melody. The uterine sounds can also provide significant stress relieving benefits [10-12]. Since the environment inside the NICU is significantly different from that of a mother's womb, it is strongly desired to decrease the NICU noise and provide the infant with the ambience of the mother's womb at the same time.

In this paper, we develop an audio-integrated active noise control system that selectively cancels the unwanted noise. In the meanwhile, an audio signal (intrauterine sound, music, or natural sound) is integrated with the ANC system to mask the residual noise and soothe the infant [13]. Carbon nanotube based transparent thin film speaker is also introduced in this paper as the actuator for the ANC system to generate the destructive secondary sound, which can significantly save the congested incubator space and without blocking the view of doctors and nurses.

II. Active Noise Control

A. ANC FXLMS algorithm

An ANC system generates an "antinoise" that acoustically cancels the unwanted primary noise based on the principle of superposition. The FXLMS algorithm is one of the most used algorithms for ANC. Fig. 1 shows the block diagram of a feedforward ANC system using the FXLMS algorithm. Here $x(n)$ is the reference signal; $y(n)$ is the desired control (speaker) signal; $y'(n)$ is the actual sound of the secondary source; $d(n)$ is the undesired primary noise; $e(n)$ is the residual noise at downstream measured by an error microphone; $x'(n)$ is the filtered version of $x(n)$; $P(z)$ is the unknown transfer function between the reference microphone and the secondary source; $S(z)$ is the dynamics from the secondary source to the error microphone; $\hat{S}(z)$ is the estimation of this secondary path, which is off-line identified following the method described in reference [14]; and $W(z)$ is the digital filter that is adapted to generate the correct control signals to the secondary source.

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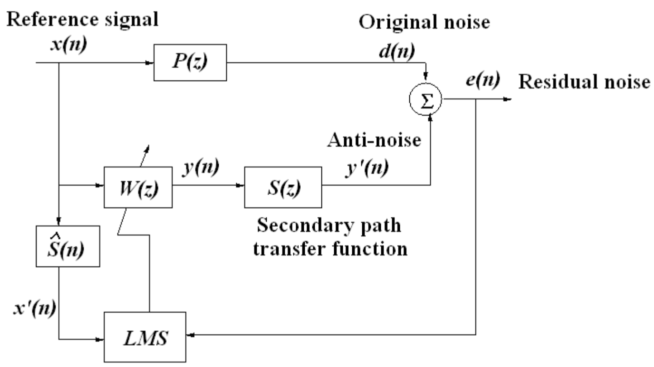

Fig. 1. Block diagram of the FXLMS feedforward control [14]

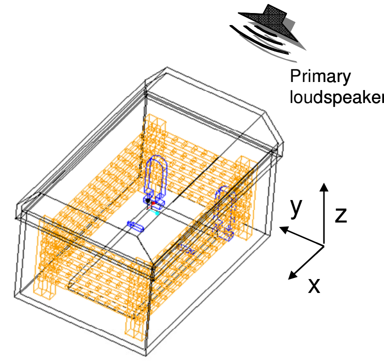

Fig .3. Illustration of the performance measurement grid

B. Experimental setup

The performance of ANC system is evaluated by conducting real-time experiments using the Giraffe® incubator from GE Healthcare. Fig. 2 shows a picture of the experimental setup, which consists of two secondary loudspeakers and two error sensors. A microphone is placed on the top of the incubator to pick up the primary noise. Thus the ANC is a 1×2×2 multiple-channel ANC system. A floating-point digital signal processor, TMS320C30, is used to conduct the real-time experiments.

To map the performance of ANC, a 3-D grid is built [15]. A measuring microphone can be attached on the 3-D grid to measure ANC performance at any uniform-spaced 3-D locations inside the incubator. The grid and the experimental parameters are fixed through all the experiments. Only the location of the measuring microphone is changed to take the measurements at different locations. Fig. 3 shows the diagram of the measurement points. It can be considered as a set of 5 parallel planes. Each plane in the z-axis contains 13x8 (104) measuring points. There is 5 cm distance between each adjacent measuring point. The z-axis starts from z = 1, which is the plane on the mattress, z = 2 plane is 5 cm above z = 1 plane and so on. So, there are a total of 13x8x5 (520) measuring points. The measurements with ANC on and ANC off are taken at all the measuring points.

Fig. 2. Experimental setup based on GE Giraffe® incubator

C. Experimental results

The performance of the ANC system is evaluated for multiple sine waves generated using the function generators. The spectra of the multiple sine waves generated at 150 Hz, 300 Hz and 520 Hz before and after cancellation at the left error microphones is shown in Fig. 4, which indicates an average noise reduction of 8-18 dB at the left error microphone [15]. Similar noise reduction level is achieved at the right error microphone.

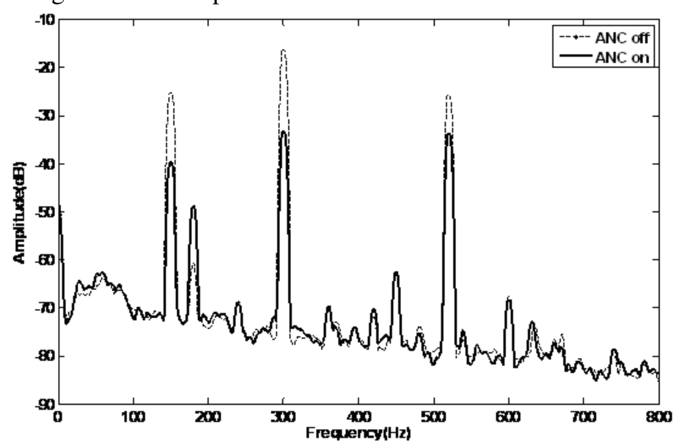

Fig. 4. Noise cancellation performance at the left error microphone for multi-frequency primary noise

To evaluate the global noise reduction performance of the ANC system, noise reduction level of each measuring point on the Fig. 3 3-D grid is recorded using 200 Hz sinusoidal wave as the primary noise. 3-D plots for different z-planes are then constructed. Fig. 5 shows the performance at z=1 plane [15]. The different colors on the color bar show the different levels of cancellation. The dark red coloration indicates the higher dB cancellations. The noise reduction performance at z=2, z=3, z=4, z=5 planes (results are not shown here for space constraints) are very similar to that of z=1. These experimental results show that there is good cancellation at almost every point inside the incubator. The noise reduction is in the range of 5-40 dB at all measuring points and the results are very encouraging.

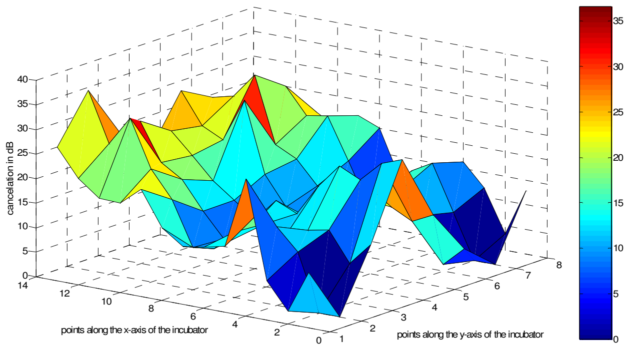

Fig. 5. Plot of net noise reduction on z=1 plane

III. AUDIO-INTERGRATED ANC SYSTEM

As discussed in Section I, an audio signal (intrauterine sound, music, or natural sound) is needed for the ANC system to mask the residual noise and soothe the infant. To achieve these goals, the ANC system should cancel the unwanted noise and not be interfered with the added audio signal. To overcome these problems, the audio component must be subtracted from the error signal before it is used to update the coefficients of adaptive filter. Fig. 6 shows the block diagram of the proposed audio integrated ANC system [15]. The audio component *a(n)* is added to the adaptive filter output *y(n)* and filtered through the secondary path *S(z)* to generate $y'(n)$. At the acoustic summing junction, the anti-noise *y'(n)* and the primary noise *d(n)* are combined to produce error signal *e_a(n)*. This is not the "true" error (residual noise) because it contains the desired audio components. Thus the audio needs to be subtracted from this error signal to provide the "true" error *e(n)* for updating ANC filter *W(z)*. It should be noted that the audio travels through the secondary path, thus it needs to be filtered through *S(z)* before it is subtracted. The error signal *e_a(n)* is expressed as [16]

$$e\_a(n) = d(n) - s(n) * [y(n) + a(n)] \quad (1)$$

The adaptive filter $\hat{S}(z)$ is used to cancel the audio interference on the error signal *e(n)*. This filter generates

$$a'(n) = \hat{s}(n) * a(n)\,. \quad (2)$$

Assuming that $S(z) = \hat{S}(z)$ and that the audio is uncorrelated with the primary noise, equation (2) can be expressed in the time domain as

$$e(n) = d(n) - y(n) * s(n) \quad (3)$$

which is the true error signal that is used to update *W(z)* using the FXLMS algorithm.

Due to the hardware constraint, the 1x1x1 FXLMS algorithm is implemented for the audio integration ANC system in the real-time experiments. The combination of two sine waves at 210 Hz and 300 Hz are used as the primary noise. Fig.7 shows the performance of the audio-integrated ANC system using time-domain waveform [15]. First the ANC is turned off and the noise picked up by the error microphone is recorded. After 70,000 samples, the ANC is turned on to reduce the noise level. Finally, at 130,000 samples the audio is played to integrate it with the existing ANC system.

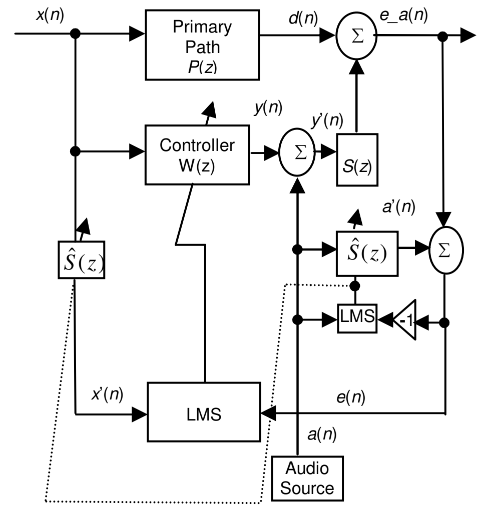

Fig. 6. Audio-integrated ANC system

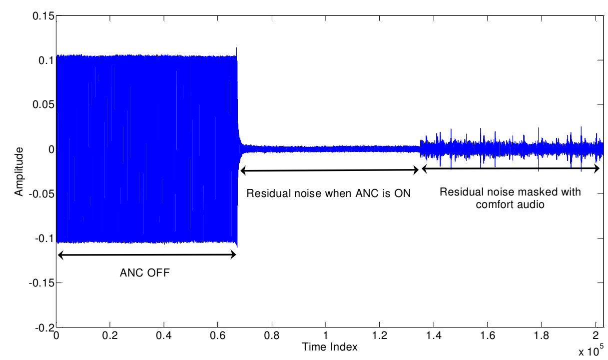

Fig. 7. Time domain representation of complete working of the audio-integrated ANC system

The spectrum of the audio integration when the ANC is on and off is shown in Fig. 8, which shows the noise reduction at 210 Hz and 300 Hz [15]. In addition, the spectrum of adding womb audio without the ANC on has high level of noise which proves annoying to the listener. The audio integration with the ANC system to mask the residual noise provides soothing environment to the infant.

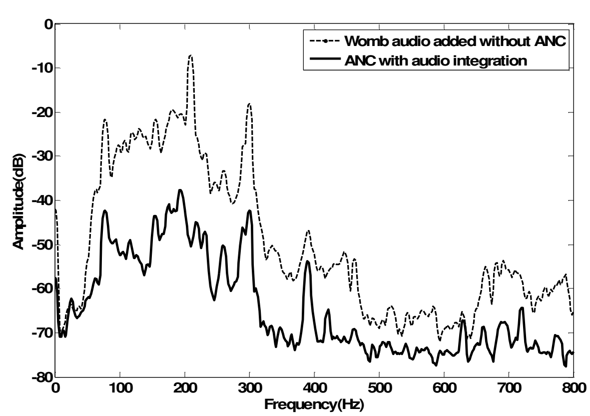

Fig. 8. Performance of ANC with and without audio-integration

IV. CARBON NANOTUBE BASED TRANSPARENT THIN FILM SPEAKER FOR INFANT INCUBATOR ANC

An ANC system needs canceling loudspeakers to generate the anti-noise sound. However, the infant incubator is space limited and cannot house large loudspeakers. Second, the enclosure of incubators must be optically transparent for medical personnel and caregivers to watch infants. Typical loudspeaker boxes may block the view at certain angles and reduce useful space. To overcome these challenges, carbon nanotube (CNT) based transparent thin film speaker is tested for infant incubator applications. This speaker consists of a piezoelectric poly (vinylidene fluoride) (PVDF) thin film coated with compliant carbon nanotube based transparent conductors [17]. The structure is illustrated in Fig. 9. When a control voltage is applied, the bending of the piezoelectric film can be used to produce the desired vibrations. Fig. 10 shows a picture of a CNT thin film speaker attached on the wall of infant incubator model.

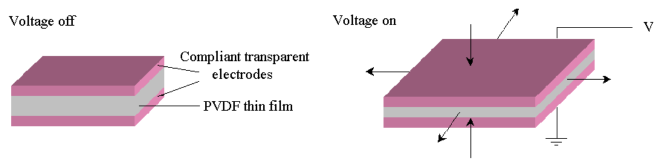

Fig. 9. The structure of the transparent thin film speaker.

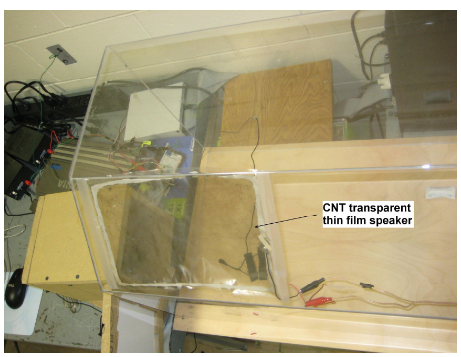

Fig. 10. A picture of CNT thin film speaker attached on an incubator model

The performance of the CNT thin film speaker with ANC system is tested on an infant incubator model using regular FXLMS algorithm. Fig. 11 shows the ANC performance in time domain for a primary noise consisted of 550 Hz and 300 Hz noise, which indicates promising results.

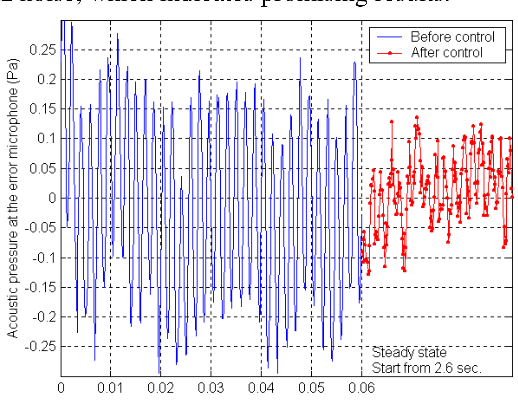

Fig. 11. ANC performance using CNT thin film speaker

V. CONCLUSION

This paper presented the audio-integrated ANC system for infant incubators. Global noise reduction was obtained inside the incubator. Experimental results also demonstrated the effectiveness of an audio integration ANC system, which selectively canceled the primary noise while keeping the added healthy audio. CNT transparent thin film speaker was also demonstrated as a promising actuator for infant incubator ANC system.

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