Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics
San Antonio, TX, USA - October 2009

Development and Applications of Active Noise Control System for Infant Incubators

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Abstract— **This paper presents the application of audio-integrated active noise control (ANC) system for infant incubators. The integrated ANC algorithm is developed to reduce harmful noise and also play healthy with intrauterine sounds inside the incubators. Real-time experiments are conducted to evaluate the performance of integrated system using a Giraffe incubator from GE Healthcare. The noise reduction achieved by ANC systems at uniformly-distributed three-dimensional locations inside the incubator is tabled and presented graphically.**

I. INTRODUCTION

Medical, therapeutic and technological advancements including the use of infant incubators in neonatal intensive care units (NICU), have significantly increased the survival of premature and ill infants [1]. 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. Over the past 20 years, the survive rate of very-low-birth-weight and premature infants has increased by more than 80% [1]. However, high level of noise inside the incubator generated by medical equipment in NICU results in numerous adverse health effects including 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 [2-8]. There is also evidence that NICU noise exposure has significant long-term consequences of hearing loss.

It is well documented that the mammalian auditory system is most vulnerable to environmental influences immediately after it first begins to function (the so-called "critical period" [9]). In humans, the critical period is approximately weeks 24-30 of gestation [10, 11], which is also the age where the most extremely premature infants can survive *ex utero.* Premature infants are therefore at high risk for environmentally-induced hearing loss. 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]. Kenworthy *et al.* found that approximately one-third of 266 NICU residents exhibited hearing impairment and/or speech language problems [5]. These adverse health effects will have lifelong consequences to the quality of life for NICU graduates.

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 [12], and/or incorporating sound containment and absorption strategies into the design of new NICUs [13]. One study that investigated the benefits of noise reduction by employing earmuffs found that reducing noise levels by 7-12 dB increased oxygen saturation levels and increased time spent asleep among premature infants [14]. However, due to the long wavelength involved in low-frequency noise, earplugs are not effective in blocking NICU noise. Bellieni *et al.* also tried to add sound-absorbing panels in the hood of an incubator to reduce the reverberating sound, resulting in about 3 dB in the noise level reduction [15]. The effect of acoustical foam on noise reduction has also been tested by Johnson [16], which shows an average of 3.27 dB reduction in noise level inside the incubator. Those methods block the view of incubator and are ineffective for low-frequency NICU noises. Since the sound level reductions of these methods are limited, the residual noise levels inside incubators are still well beyond the 45 dB, a limit recommended by the American Academy of Pediatrics [17-19]. It is therefore of the utmost importance to develop new approaches that can significantly reduce noise levels inside incubators.

In summary, the performance of passive techniques in low-frequency range is limited. Furthermore, most passive techniques either occupy limited incubator space or block the view of infant by caregivers, or both. These difficulties motivated the development of active noise control (ANC) systems [20] to cancel the low-frequency noise inside the incubators [21-23].

This paper develops audio-integrated ANC systems to reduce harmful noise and play intrauterine sounds inside the incubators [24]. The single-channel and multi-channel ANC algorithms are developed and implemented using a digital signal processor for real-time experiments based on a real Giraffe incubator.

II. ACTIVE NOISE CONTROL ALGORITHMS AND EXPERIMENTS

This section presents single-channel and multi-channel ANC algorithms that are developed for infant incubators, and

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conducts real-time experiments to evaluate their performance for noise reduction.

A. Single-channel ANC systems

From the spectrum of incubator noise, 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 [20]. 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) $e(n)$.

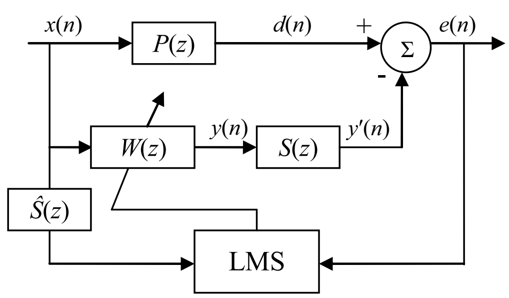

Fig.1 Single-channel ANC system using the FXLMS algorithm [20].

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 [27]. 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 (or training) technique [20]. This preliminary model needs to be updated during the on-line ANC operation if the environment changes. Section IV.C will show that the audio-integrated ANC systems can effectively model the secondary path on-line using the adaptive filter $\hat{S}(z)$, thus further enhance the performance of ANC algorithm in time-varying environment.

The residual noise can be described as

$$e(n) = d(n) - s(n) * y(n), \quad (1)$$

where $s(n)$ is the impulse response of the secondary path $S(z)$, and * denotes linear convolution. The adaptive filter output is computed as

$$y(n) = \mathbf{w}^T(n)\mathbf{x}(n), \quad (2)$$

where $\mathbf{w}(n) = [w_0(n)\ w_1(n)\ ...\ w_{L-1}(n)]^T$ is the coefficient vector of $W(z)$ at time n, $\mathbf{x}(n) = [x(n)\ x(n-1)\ ...\ x(n-L+1)]^T$ is the input signal vector, and L is the filter length. The adaptive filter is updated by the FXLMS algorithm expressed as

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \mu\mathbf{x}'(n)e(n), \quad (3)$$

where $\mathbf{x}'(n) = [x'(n)\ x'(n-1)\ ...\ x'(n-L+1)]^T$ is the filtered signal vector and μ is the step size (or convergence factor) that determines the transient and steady-state performance of the algorithm. The filtered signal $x'(n)$ is obtained by filtering the reference signal $x(n)$ by the secondary-path model $\hat{S}(z)$ expressed as

$$x'(n) = \hat{s}(n) * x(n), \quad (4)$$

where $\hat{s}(n)$ is the impulse response of $\hat{S}(z)$.

Real-time experiments of the single-channel ANC system are conducted in Section III.D 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 achieved noise cancellation is not sufficient. Thus multi-channel ANC systems are required to create a larger size of quiet zone with higher noise reduction.

B. Multi-channel ANC systems

A multi-channel ANC system uses multiple secondary loudspeakers and error sensors to produce a larger quiet zone. This paper uses a two-channel feedforward ANC system called the 1x2x2 FXLMS algorithm [20] with a single reference microphone, two secondary loudspeakers, and two error microphones for real-time experiments.

Fig. 2 shows a detailed block diagram of the two-channel ANC system with a single reference signal $x(n)$. The primary paths $P_1(z)$ and $P_2(z)$ are from the noise source to both the error microphones; the primary noises to be cancelled are $d_1(n)$ and $d_2(n)$; and the residual noises are $e_1(n)$ and $e_2(n)$. The canceling signals $y_1(n)$ and $y_2(n)$ are generated by the adaptive filters $W_1(z)$ and $W_2(z)$, respectively, to drive the secondary loudspeakers. The secondary paths $S_{11}(z)$ and $S_{21}(z)$ are from $y_1(n)$ to the error signals $e_1(n)$ and $e_2(n)$, respectively; and $S_{12}(z)$ and $S_{22}(z)$ are from $y_2(n)$ to the error signals $e_1(n)$ and $e_2(n)$, respectively.

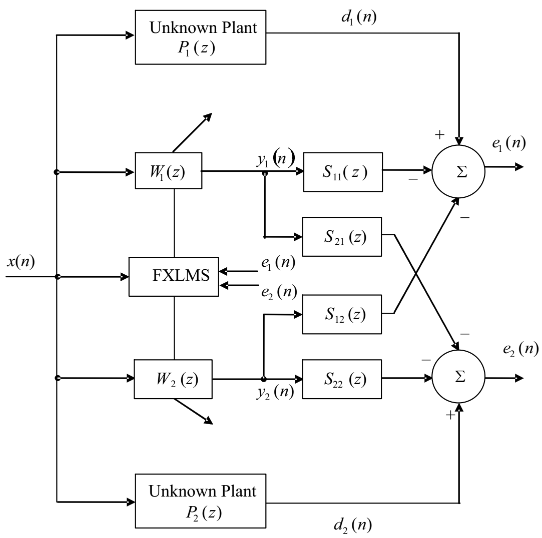

Fig. 2 An example of two-channel ANC system with the 1x2x2 FXLMS algorithm [20].

The 1x2x2 FXLMS algorithm can be summarized as follows [20]. The canceling signals are computed as

$$y_i(n) = \mathbf{w}_i^T(n)\mathbf{x}(n), \quad i = 1,\ 2. \qquad (5)$$

The adaptive filters are updated by the 1x2x2 FXLMS algorithm as

$$\mathbf{w}_i(n+1) = \mathbf{w}_i(n) + \mu\left[e_1(n)\mathbf{x}(n) * \hat{s}_{1i}(n) + e_2(n)\mathbf{x}(n) * \hat{s}_{2i}(n)\right], \quad i = 1,\ 2, \qquad (6)$$

where $\hat{s}_{11}(n)$ and $\hat{s}_{21}(n)$ are the impulse responses of secondary-path models $\hat{S}_{11}(z)$ and $\hat{S}_{21}(z)$, respectively, and $\hat{s}_{12}(n)$ and $\hat{s}_{22}(n)$ are the impulse responses of models $\hat{S}_{12}(z)$ and $\hat{S}_{22}(z)$, respectively.

Compared with the single-channel ANC system shown in Fig. 1, 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.

C. Experimental setup

The performance of ANC systems is evaluated by real-time experiments using the Giraffe incubator from GE Healthcare. Fig. 3 shows the experimental setup for the two-channel ANC systems, which consists of two secondary loudspeakers and two error sensors. An independent loudspeaker at the right side (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 (right side) to pick up the primary noise. Two loudspeakers are placed at the two (right) corners of the incubator to generate the anti-noise. Two error microphones (black) are placed on the mattress, and two extra microphones (will be shown in Fig. 4) are used to measure the noise levels inside the incubator at different locations when the ANC is turned on and off. The primary microphone has a switch to turn on and off of the ANC by gradually producing zero output and freezing the filter coefficients, see equations (2) and (3) if $x(n) = 0$. Both single-channel and multi-channel ANC algorithms are implemented on the floating-point digital signal processor, TMS320C30, for real-time experiments.

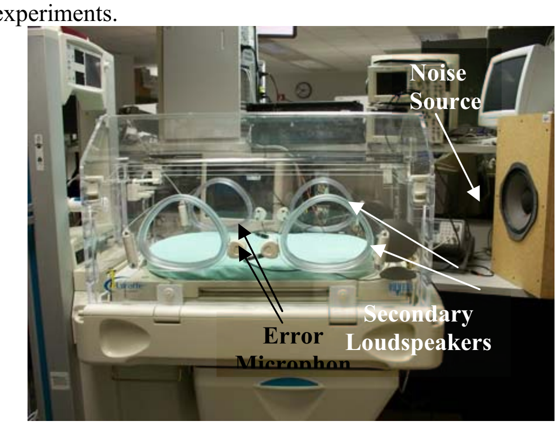

Fig. 3 Experimental setup for two-channel ANC systems using the Giraffe incubator.

To measure ANC performance at uniformly-spaced three-dimensional (3-D) locations inside the incubator, a 3-D grid with movable bars to hold measuring microphones is built. As shown in Fig. 6, two measuring microphones (on the left side of top bars) are attached on the grid at different locations with 5 cm distance between two adjacent points. By moving the bars and microphone locations, we can measure the performance at every grid's location inside the incubator with the resolution of 5 cm. The experimental parameters (such as filter length, step size, amplifier gain, etc.) are fixed for all the experiments, but the locations of the measuring microphone are changed for repeated measurements.

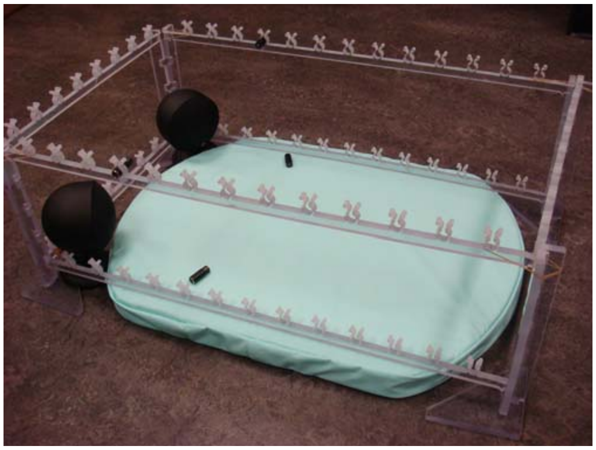

Fig. 4 The grid for measuring real-time ANC performance at uniformly-spaced 3-D locations inside the incubator. This grid is custom-made to fit the incubator shown in Fig. 3.

The measuring points on the 3-D grid shown in Fig. 4 can be indicated by x-y-z axis. The grid has 5 different horizontal planes along the z-axis. Each plane is a two-dimensional plane with 13 measuring points on the x-axis and 8 points on the y-axis, thus contains 13x8 (= 104) measuring points. There are total of 13x8x5 (=520) measuring points uniformly-distributed inside the incubators. The z-axis starts from z = 1, which is the plane 5 cm above the mattress, z = 2 plane is 5 cm above the z = 1 plane, and so on.

D. Experiment results

This section presents the noise cancellation achieved by different ANC algorithms at both the error and measuring microphones at uniformly-distributed points inside the incubator. The spectrum plots are obtained using a Hewlett-Packard spectrum analyzer (35670A) with the averaging function, and plotted by a MATLAB program.

1) Single-channel ANC systems

The performance of single-channel broadband feedforward ANC system is evaluated using a 200 Hz tone as the primary noise. Refer to Fig. 3, only a single secondary loudspeaker is placed at the right side of the incubator, and only one error microphone is used. The spectra of signals measured at the error microphone before (ANC OFF) and after (ANC ON) the operation of ANC system are shown in Fig. 5, which shows a significant noise reduction can be achieved by the single-channel ANC system at the error microphone location.

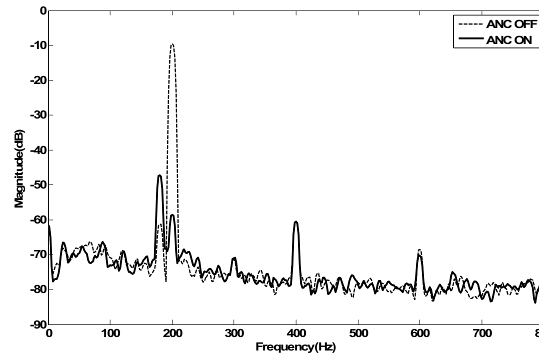

Fig. 5 Noise cancellation achieved by the single-channel ANC system at the error microphone when the primary noise is a 200 Hz tone.

The next set of experiments using the same 200 Hz tone 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 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.

As discussed in Section II.C, each plane has 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 [24]. Since the plane at z = 1 (5 cm above the mattress) is most close to the ears of infants, this paper only presents the noise reduction at these uniformly-spaced 104 points on the z = 1 plane in Table I. There are two points (x/y= 1/4 and 1/5) in Table I without measurements because the secondary loudspeaker is located there. The noise reduction of 15-20 dB can be achieved at many points, and higher noise cancellation points are away from the loudspeaker (indicated by larger values of x). At some measuring points close to the loudspeaker (e.g. (1,3) and (1,6)), there is increase in the noise levels indicated by negative numbers.

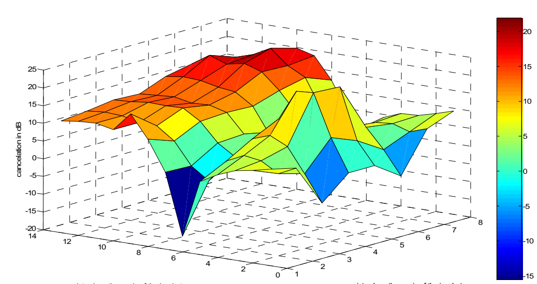

Fig. 6 A 3-D plot of net noise reduction on the z = 1 plane for the single-channel ANC system.

The net noise reduction at different locations on the z = 1 plane is presented graphically in Fig. 8. Different colors (indicated by the color bar) show different levels of noise reduction, where the dark red indicates higher dB cancellation. The higher noise cancellation locations are at x = 10, 11, 12, and 13 with average noise cancellation gain 15.1457dB, where are away from the secondary loudspeaker. Therefore, the infant should be placed in the incubator with the head away from the loudspeaker, which is also desired for safety concerns. However, the quiet zone size and noise reduction created by the single-channel ANC system are still relatively small, thus give the motivation of using multi-channel ANC systems.

2) Multi-channel ANC systems

In multi-channel ANC system with the 1x2x2 FXLMS algorithm, performance at the left and right error microphones are evaluated for the primary noise contains three tones at 150 Hz, 300 Hz and 520 Hz. The spectra of error signals before and after noise cancellation at the left and right error microphones are measured, and Fig. 7 shows the noise reduction at the right error microphone as an example. Noise reduction for all three tones can be obtained, but the residual tonal components are still noticeable.

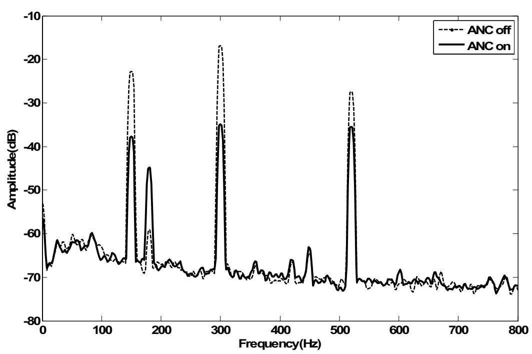

Fig. 7 Noise cancellation at the right error microphone for the multi-channel ANC system.

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. The experimental setup is shown in Fig. 3, 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 520 measuring points are reported in [24]. The net noise reduction on the z =1 plane is shown in Fig. 8. The higher noise cancellation can be obtained at the locations of x = 9, 10, 11, 12, and 13 with average noise cancellation gain 22.6540dB. 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.

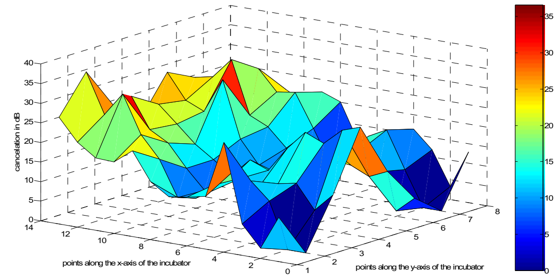

Fig. 8 A 3-D plot of noise reduction on the z = 1 plane for the 1x2x2 FXLMS algorithm.

The performance of the single-channel and multi-channel ANC systems can be compared from Tables I and II, or from Fig.6 and 8. The single-channel ANC system shows good performance only at the locations close to the error microphone; while the 1x2x2 FXLMS algorithm achieved higher noise reduction and creates a larger quiet zone with higher noise reduction than the single-channel ANC system, especially at locations that are away from the loudspeakers. Therefore, the feet of the baby are placed at the side with loudspeakers so the head location will be in the quiet zone of x = 9, 10, 11 and 12 for the best noise reduction.

III. CONCLUSIONS

This paper presented the development, application and real-time experiment of audio-integrated ANC systems using the real incubator to reduce the high levels of noise. Experimental results showed the incubator noise can be significantly reduced using the developed ANC algorithms.

REFERENCES

[1] U. S. Department of Health and Human Services, "Neonatal intensive care – A history of excellence," *NIH Publication*, No. 92-2786, 1992.

[2] Jacobs, S. E., O'Brien, K., Inwood, S., Kelly, E. N. and Whyte, H. E., "Outcome of infants 23-26 weeks' gestation pre and post surfactant," *Acta Paediatr.*, vol. 89, pp. 959-965, 2000.

[3] Lorenz, J. M., "The outcome of extreme prematurity," *Semin. Perinatol.*, vol. 25, pp. 348-359, 2001.

[4] Stennert, E., Schulte, F. J., Vollrath, M., Brunner, E. and Frauenrath, C., "The etiology of neurosensory hearing defects in preterm infants," *Arch Otorhinolaryngol*, vol. 221, pp. 171-182, 1978.

[5] Kenworthy, O. T., Bess, F. H., Stanhlman, M. T. and Lindstrom, D. P., "Hearing, speech, and language outcome in infants with extreme immaturity," *American J. Otology*, vol. 8, pp. 419-425, 1987.

[6] Long, J. G., Lucey, J. F. and Philip, A. G., "Noise and hypoxemia in the intensive care nursery," *Pediatrics*, vol. 65, pp.143-145, 1980.

[7] Trapanotto, M., Benini, F., Farina, M., Gobber, D., Magnavita, V. and Zacchello, F., "Behavioral and physiological reactivity to noise in the newborn," *J. Pediatric Child Health*, vol. 40, pp. 275-281, 2004.

[8] Philbin, M. K. and Klaas, P., "Hearing and behavioral responses to sound in full-term newborns," *J. Perinatol.* vol. 20, pp. S68-76, 2000.

[9] Saunders, J. C. and Chen, C. S., "Sensitive periods of susceptibility to auditory trauma in mammals," *Environ. Health Perspect*., vol, 44, pp. 63-66, 1982.

[10] Birnholz, J. C. and Benacerraf, B. R., "The development of human fetal hearing," *Science*, vol. 222, pp. 516-518, 1983.

[11] Lary, S., Briassoulis, G., de Vries, L., Dubowitz, L. M. and Dubowitz, V., "Hearing threshold in preterm and term infants by auditory brainstem response," *J. Pediatr*., vol. 107, pp. 593-599, 1985.
[12] Kent, W. D., Tan, A. K., Clarke, M. C. and Bardell, T., "Excessive noise levels in the neonatal ICU: Potential effects on auditory system development," *J. Otolaryngol.*, vol. 31, pp. 355-360, 2002.
[13] Philbin, M. K. and Evans, J. B., "Standards for the acoustic environment of the newborn ICU," *J. Perinatol*., vol. 26, Suppl. 3, pp. S27-30, 2006.
[14] Zahr, L. K. and de Traversay, J., "Premature infant responses to noise reduction by earmuffs: Effects on behavioral and physiologic measures," *J. Perinatol*., vol. 15, pp. 448-455, 1995.
[15] Bellieni, C. V., Buonocore, G., Pinto, I., Stacchini, N., Cordelli, D. M. and Bagnoli, F., "Use of sound-absorbing panel to reduce noisy incubator reverberating effects," *Biol. Neonate*, vol. 84, pp. 293-296, 2003.
[16] Johnson, A. N., "Neonatal response to control of noise inside the incubator," *Pediatr. Nurs.* vol. 27, pp. 600-605, 2001.
[17] American Academy of Pediatrics, Committee on Environmental Health, "Noise: A hazard for the fetus and newborn," *Pediatrics*, vol. 100, pp. 724-727, 1997.
[18] Robertson, A., Cooper-Peel, C. and Vos, P., "Sound transmission into incubators in the neonatal intensive care unit," *J. Perinatol.*, vol. 19, pp. 494-497, 1999.
[19] Carvalho, W. B., Pedreira M. L. G. and de Aguiar M. A. L., "Noise level in a pediatric intensive care unit," *Journal de Pediatria*, vol. 81, pp. 495-498, 2005.
[20] Kuo, S. M. and Morgan, D. R., "Active noise control: A tutorial review," *Proc. of the IEEE*, vol. 87, pp. 943-973, 1999.
[21] Thanigai, P., Kuo, S. M. and Yenduri, R., "Nonlinear active noise control for infant incubators in neo-natal intensive care units," in *Proc. ICASSP*, 2007, pp. 109-112.
[22] Thanigai, P. and Kuo, S. M., "Intrauterine acoustic embedded active noise controller," in *Proc. IEEE Int. Conf. on Control Applications*, 2007, pp. 1359-1364.
[23] Liu, L., Gujjula, S., Thanigai, P. and Kuo, S. M., "Still in womb: Intrauterine acoustic embedded active noise control for infant incubators," *Advances in Acoustics and Vibration*, vol. 2008, article ID 495317, 2008.
[24] Gujjula, S., *Real-Time Audio Integrated Active Noise Control System for Infant Incubators*, MS Thesis, Northern Illinois University, August 2008.
[25] "The miracle baby sleep system," article from http://www.babysleepsystem.com/index.htm
[26] Morgan, D. R., "An analysis of multiple correlation cancellation loops with a filter in the auxiliary path," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. ASSP-28, pp. 454-467, 1980.
[27] Gan, W. S. and Kuo, S. M., "An integrated audio and active noise control headsets," *IEEE Trans. Consumer Electronics*, vol. 48, pp. 242-246, 2002.