Wireless Communication Integrated Hybrid Active Noise Control System for Infant Incubators

Lichuan Liu, Lilin Du and Ajit Kolla
Department of Electrical Engineering
Northern Illinois University
DeKalb, IL, 60115, USA
lilindu0420@gmail.com, liu@niu.edu and kolla@gmail.com

***Abstract*—This paper proposed a wireless communication integrated hybrid active noise control (ANC) system that will reduce the level of noise in an infant incubator at the infant's ear and provide two-way wireless communication between infant and his/her parents/caregivers both inside and outside the Neonatal intensive care unit (NICU). The proposed system use ANC technique to reduce the noise. The wireless communication integrated system will be used to release stress, improve bonding and improve language development. The real-time experiments show that the proposed system can significantly reduce the noise exposure to the infants being placed in infant incubators with consequent reduction the health risk induced by high-level noise in NICU and provide bonding opportunities for infants and their parents.**

Keywords*—** *Neonatal intensive care unit, infant incubator, active noise control,** *wireless communication, hybrid, FXNLMS algorithm.*

I. Introduction

Newborns in need of intensive medical attention are often admitted into the NICU, which combines advanced technology and trained healthcare professionals, as shown in Time Magazine (June 2, 2014) [1]. Incubators have greatly increased the survival of very low birth weight and premature infants. However, according the article published in Acta Paediatr (2000) and other papers, high levels of noise in the NICU have been shown to cause numerous adverse health effects, including sleep disturbance and other forms of stress, as well as alterations in physiological responses such as heart and respiratory rate, blood pressure and oxygen saturation [2-9]. Moreover, even normal levels of ambient noise may pose considerable risk to the most premature infants. The mammalian auditory system is most vulnerable to environmental influences immediately after the time that it first begins to function (the so-called "critical period [10]"). In humans, the critical period corresponds to weeks 24-30 of gestation [11, 12], which is also the age that the most extremely premature infants can survive ex utero. These micro-preemies are, therefore, at high risk for environmentally-induced hearing loss. Based on research results published in Semin Perinatol (2001), approximately 52% of NICU infants exhibit hearing loss [4, 5] of different levels and 3-5% of them become profoundly deaf [3]. Unfortunately, there are few developed methods that are effective in reducing incubator noise, particularly impulse noise. Most attempts to improve the acoustic environment of the NICU have focused on reducing staff activities [13], and/or incorporating sound containment and absorption strategies into the design of NICUs [14], for example, earmuffs [15], sound-absorbing panels [16], and acoustical foam [17] are used to passively reduce the noise level in the incubator. These methods block the incubator view from caregivers and are also ineffective for reducing low-frequency NICU noises and impulse noise. Therefore, it is extremely important to reduce noise level inside incubator decrease the risk of health impairment and disability due to the high noise level. Unlike conventional passive noise control methods, the ANC system generates an 'anti-noise', which has the same amplitude but opposite phase from the unwanted noise and acoustically cancels the unwanted noise based on the principle of superposition [18]. ANC systems have been developed for a variety of applications, such as heating, venting, air-conditioning systems, engine exhaust systems, and ANC headphones [18-20]. Preliminary work on this project [21-25] showed that these traditional ANC systems cannot be applied directly to incubators without modification due to complicated noise models in the NICU. It has multiple unexpected noise sources from both outside and inside the incubator [2]. Therefore, we propose the application of multi-channel hybrid ANC algorithms that combine feed-forward and feedback ANC algorithms for incubator to cancel both inside and outside noises.

On the other hand, preterm infants begin to make vocalizations at 32 weeks and significantly increase their number of vocalizations over time. The regressions clearly demonstrate at both 32 and 36 weeks that the more adult language the preterm infant is exposed to in the NICU, the greater the number of reciprocal vocalizations, which can be found in the research paper published in Pediatrics(2011) [26]. In addition, preterm infants vocalize more when their parents are visiting, with increases in the number of vocalizations by as much as 129% when a parent is present. It is the powerful impact that parent talk has on the appearance and increment of vocalizations in preterm infants in the NICU [26]. Moreover, bonding is the most important relationship in a child's life. Healthy bonding experiences during infancy provide the solid foundation for future healthy relationships, according to Obeidat's work published in J Perinat Educ. (2009) [27]. Unfortunately, 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 critical to provide

This project is supported by NSF STTR grant #1448907

communication for NICU babies and their parents both inside and outside NICU in order to improve language development and bonding. In addition, two way communications can help newborns inside the incubators to release stress and benefit the new mothers, such as, preventing postpartum depression, as shown in the research paper in Journal of Clinical Psychology in Medical Settings (2010) [28].

Our approach will focus on reduce the noise level inside incubator and provide the language development stimulus and bonding opportunities at the same time. The advantages of the integrated ANC system are summarized as follows: 1) it can reduce the risk of health impairments and disability for infants caused by high level noise, 2) it can provide positive speech stimuli and/or the comfort audio to infants, 3) it can boost bonding opportunities between infant and their parents, and 4) it integrates with the existing ANC's audio hardware such as amplifiers and loudspeakers for saving overall system cost.

II. System Statement

The proposed ANC system including two sub systems, as shown in Fig. 1, the multi-channel hybrid ANC system which is used to reduce the harmful noises and the wireless communication system which is used to provide the bidirectional communication channel between the infant and the parents/caregivers.

A. *Multi-channel hybird ANC system*

In Fig. 1, assume that J reference sensors, K secondary sources and M error sensors are used.

The reference signal has J channels, which can be expressed in vector form as
$x(n) = [x_1^T(n)\ \ x_2^T(n)\ \ \ldots\ \ x_J^T(n)]^T$, where $x_j(n)$ is the jth channel reference signal vector of length L
$x_j(n) = [x_j(n)\ \ x_j(n-1)\ \ \ldots\ \ x_j(n-L+1)]^T$. The length L is selected so that the primary path can be adequately modeled.

The secondary sources have K channels,
$\mathrm{y}(n) = [y_1(n)\ \ y_2(n)\ \ \ldots\ \ y_k(n)]^T$, which is the signal of kth output channel at time n. The error signals have M channels,
$\mathrm{e}(n) = [e_1(n)\ \ e_2(n)\ \ \ldots\ \ e_m(n)]^T$, where $e_m(n)$is the error signal of mth error channel at time n.

The primary noise and the estimated primary noise have M channels which can be expressed by

$$\mathbf{d}(n) = [\mathbf{d_1}(n)\quad \ldots\quad \mathbf{d_M}(n)]^T + \mathrm{v}(n) = \begin{pmatrix} p_{11}(n) & \cdots & p_{1J}(n) \\ \vdots & \ddots & \vdots \\ p_{M1}(n) & \cdots & p_{MJ}(n) \end{pmatrix} * \begin{pmatrix} \mathrm{x}_1^T(n) \\ \vdots \\ x_J^T(n) \end{pmatrix} + \mathrm{v}(n) \tag{1}$$

where $P_{mj}(n)$ is the impulse response function with length L from the jth reference sensor to the mth error sensor, $v(n)$ is the noise vector picked up by error microphones, which is the inside incubator noise that is not sensed by the reference microphones.

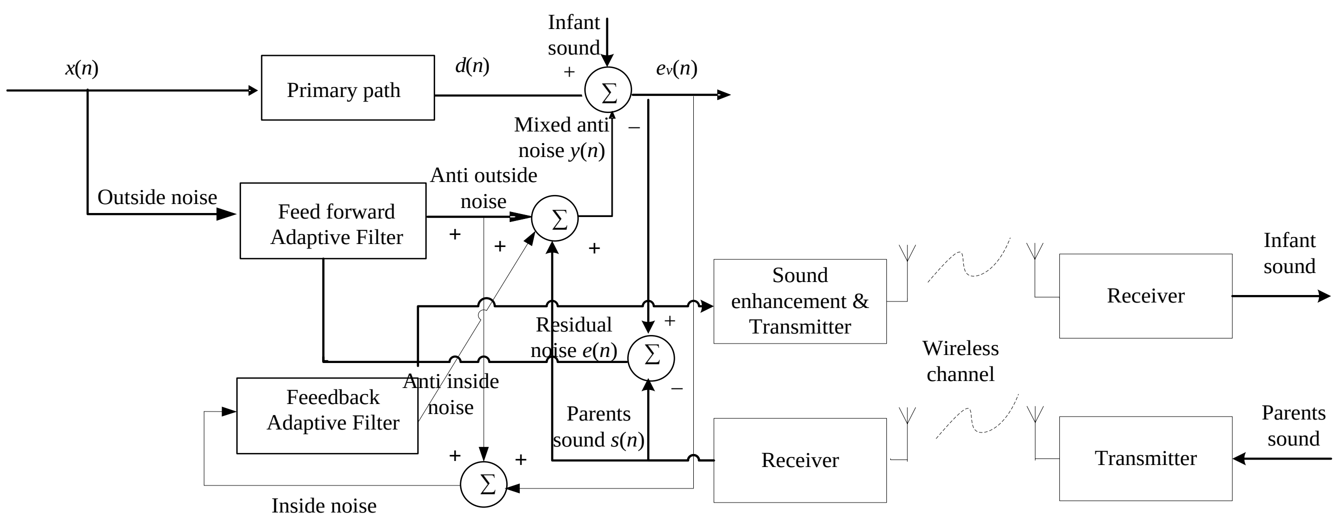

Fig. 1 Block diagram of wireless communication integrated multi-channel hybrid ANC

Matrix $\mathbf{S}(n)$ is the secondary path impulse response function.

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

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

Matrix $\mathbf{A}$(n) is the feedforward adaptive FIR filter impulse response function, which has J input, K outputs, and length L, $\mathbf{A}(n) = [\mathbf{A}_1^T(n)\ \mathbf{A}_2^T(n)\ \cdots\ \mathbf{A}_K^T(n)]^T$, where $\boldsymbol{A_k}(n) = [\mathbf{A}_{k,1}^T(n)\ \mathbf{A}_{k,2}^T(n)\ \cdots\ \mathbf{A}_{k,J}^T(n)]^T$, k = 1, 2, …, K is the weight vector of the kth feedforward FIR adaptive filter with J input signals with $\mathbf{A}_{k,j}(n) = [a_{k,j,1}(n)\ a_{k,j,2}(n)\ \cdots\ a_{k,j,L}(n)]^T$ is the feedforward FIR weight vector from the jth input to the kth output.

Matrix $\mathbf{F}$(n) contains the impulse response function of feedback adaptive FIR filter $\mathbf{F}(n) = [\mathbf{F}_1^T(n)\ \mathbf{F}_2^T(n)\ \cdots\ \mathbf{F}_K^T(n)]^T$ with its components defined similarly as $\mathbf{A}(n)$.

The secondary source is driven by the summation of the feedforward and feedback filter output. That is

$$y_k(N) = \sum_{j=1}^{J} \mathbf{x}_j^T(n)\mathbf{A}_{kj}(n) + \sum_{m=1}^{M} \mathbf{d}_m^T(n)\mathbf{F}_{km}(n) = \mathbf{x}_j^T(n)\mathbf{A}_k(n) + \mathbf{D}^T(n)\mathbf{F}_k(n) \quad (2)$$

The estimated primary noise $\tilde{\mathbf{d}}(n+1)$ can be obtained by

$$\tilde{\mathbf{d}}(n+1) = \mathbf{e}(n) - \mathbf{y}'(n) = \mathbf{e}(n) - \hat{\mathbf{S}}(n) * \mathbf{y}(n) \quad (3)$$

where * denotes the convolution operation.

The error vector measured by M sensors is

$$\mathbf{e}(n) = \mathbf{d}(n) + \boldsymbol{y}'(n) = \mathbf{d}(n) + \mathbf{S}(n) * [\mathbf{X}^T(n)\mathbf{A}(n) + \mathbf{D}(\mathbf{n})\mathbf{F}(n)] \quad (4)$$

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

Then we use filtered-x least mean square (FXLMS) algorithm to update the coefficients of the adaptive filters

$$\mathbf{A}(n+1) = \mathbf{A}(n) - \mu\mathbf{X}'(n)\mathbf{e}(n) \quad (5a)$$

$$\mathbf{F}(n+1) = \mathbf{F}(n) - \mu\tilde{\mathbf{D}}'(n)\mathbf{e}(n) \quad (5b)$$

and the estimated reference signals are

$$\mathbf{X}'(n) = [\mathbf{S}(n) * \mathbf{X}^T(n)]^T \quad (6)$$

Similar, we have $\tilde{\mathbf{D}}'(n)$ in following, see (5b)

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

with similarly defined $\tilde{\mathbf{d}}'_{km}(n)$. Then, we have

$$\mathbf{A}_k(n+1) = \mathbf{A}_k(n) - \mu\sum_{m=1}^{M}\mathbf{x}'_{km}(n)e_m(n) \quad (7)$$

and it can be further expended as

$$\mathbf{A}_{k,j}(n+1) = \mathbf{A}_{k,j}(n) + \mu\sum_{m=1}^{M}\mathbf{x}'_{km}(n)e_m(n) \quad (8)$$

The drawback of LMS algorithm is that it varies dramatically when input x'(n) changes a lot. It is hard to choose a constant for step size μ to keep robust at all time. Filtered-x normalized least mean square (FXNLMS) algorithm develops from FXLMS but solves the problem by normalizing the power of input signal $\mathbf{x}$(n) [29]. It can be expressed as

$$\mu = \frac{1}{\|\mathbf{x}(\boldsymbol{n})\|^2} \quad (9)$$

By choosing FXNLMS algorithm, the ANC system is stable and effective. In similar fashion, we can also obtain a scalar version of (5b).

B. *Wireless communication integration*

In addition to reducing harmful noise, the desired speech signal, such as parents' voice is picked up, processed, and played to the 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. 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.

The speech signal $s(n)$ is added to the adaptive filter output $y(n)$ to generate anti-noise. 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 speech signal. To avoid the interference of the speech on the performance of ANC, the speech signal $s(n)$ subtracted from $e_v(n)$ to get the true error signal $e(n)$ for updating the adaptive filter.

$$e_v(n) = d(n) - [y(n) + s(n)] \quad (10)$$

The actual error signal e(n) is expressed as

$$e(n) = e_v(n) - s(n) \quad (11)$$

Therefore, the speech components won't degrade the performance of the noise control filter, and the ANC system won't cancel the speech signal.

III. REAL-TIME EXPERIMENT AND RESULTS

A. Real-time experiment setup

The real time experiments are performed in GE Giraffe OmniBed Incubator which is shown in the Fig 2. The experimental set up for a Hybrid 1x2x2 ANC system with one reference microphone, two secondary loud speakers and two error microphones is shown in Fig. 3.

Fig.2. GE Giraffa OmniBed Infant incabator

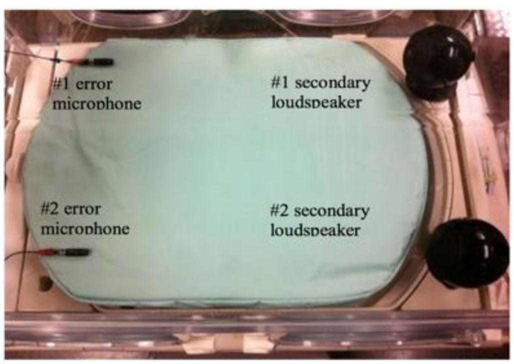

Fig.3. Real-time experiment setup

From the previous work and analysis of NICU noise in [30], it is stated that the noise power is large and predominant at frequencies 240Hz, 500Hz and 750Hz. A primary loudspeaker is driven by a R&S UPV Audio Analyzer which generates a multi-sine wave containing 240Hz, 500Hz and 750Hz. The amplitudes of these tones are chosen such that 240Hz has the highest amplitude of 1.5V, 1.3V for 500Hz and the least amplitude of 1.0V for 750Hz. This primary loudspeaker acts as a noise source that reflects the various medical equipment in NICU environment. A reference microphone that is placed along the in-line corner of the incubator is used to capture the primary noise. The anti-noise is generated by two secondary loudspeakers placed at two opposite corners inside the incubator. Two error microphones placed at two sides of the mattress pick up the residual noise that is used to adapt the filter.

TMS320C6713 DSP Starter Kit package provided by Spectrum Digital, Inc is used to implement the ANC algorithms used in this paper. DSK6713IF-A daughter card and MSPAMP800 amplifier board developed by Hiratsuka Engineering Co., Ltd. MSPAMP800 have been used for the I/O and amplifier for the presented system.

B. Experiment results for Noise reduction

To test performance of HANC system, two kinds of noise are used. First, we only use the single sinusoidal wave at 240 Hz which is the strongest one among the three dominate frequencies.

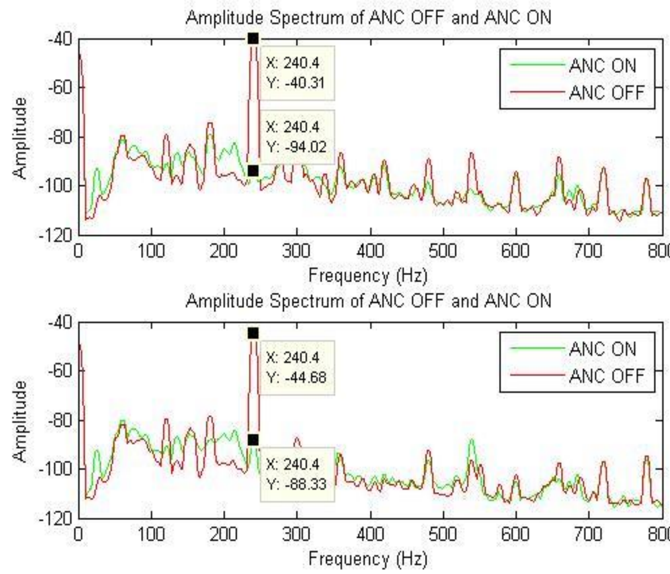

Fig. 4 Amplitude spectrum of ANC OFF and ANC ON for 240 Hz sinusoidal wave

Side	ANC OFF (dB)	ANC ON (dB)	Cancellation (dB)
Left	-40.31	-94.02	53.71
Right	-44.68	-88.33	43.65

Table. 1 Cancellation result for 240 Hz sinusoidal wave

The spectra of error signals before and after ANC at the left and right error microphones are shown in Fig. 4. The noise attenuation gains can be found in Table 1. Clearly, there is satisfactory reduction of the single sinusoidal noise source. Average noise cancellation is 53 dB at the left error microphone, and 43 dB at the right error microphone.

Frequency(Hz)	ANC OFF(dB)	ANC ON(dB)	Cancellation(dB)
240	-45.3	-91.33	46.3
500	-49.15	-87.17	38.02
750	-45.69	-73.31	27.62

Table. 2 Cancellation result for multi sinusoidal waves.

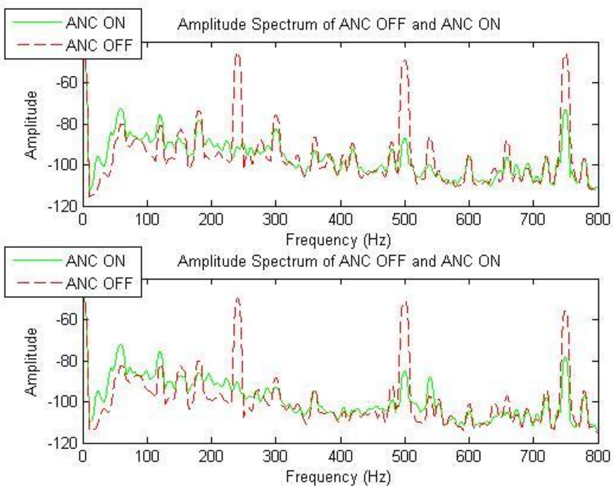

Fig. 5 Amplitude spectrum of ANC OFF and ANC ON for multi sinusoidal waves at 240 Hz, 500 Hz and 750 Hz

Then we use a multi-sine wave containing 240Hz, 500Hz and 750Hz as the noise source for the experiment. The noise cancellation performance can be observed from Fig. 5 and Table 2. Average noise cancellation is 46 dB, 38dB and 27dB at 240Hz, 500Hz and 750Hz. It is shown that ANC system has better cancellation for lower frequency noises.

C. Wireless communication integration

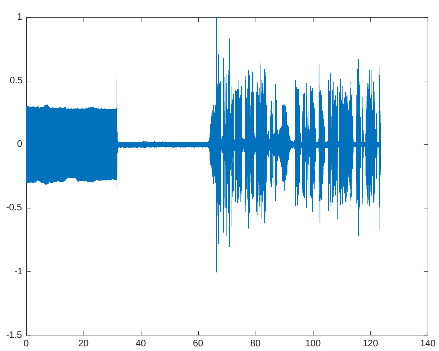

Fig. 6 Sound recorded of the wireless communication integrated ANC system (ANC OFF, ANC ON and ANC ON with integration)

Figure 6 show the time-domain waveform of the signal recorded at left error microphone demonstrating the complete operation of the voice-integrated ANC system respectively. The noise picked up by the error microphones is recorded for 31 seconds during ANC OFF. Then, ANC is turned ON and the signal is recorded for 32 seconds. Finally, after 63 seconds, the sample voice signal is played and given to the processor such that it is integrated with the ANC system.

The spectrograms for the recorded waveforms are shown in Fig. 7. The spectrograms show three frequency components 240Hz, 500Hz and 750Hz indicated by a dark red color during the first part, there is only speech signal, the second part is speech and noise with the ANC is OFF. Then the intensity levels are decreased representing the ANC ON condition at the third part. It can be observed that integration of parents' voice does

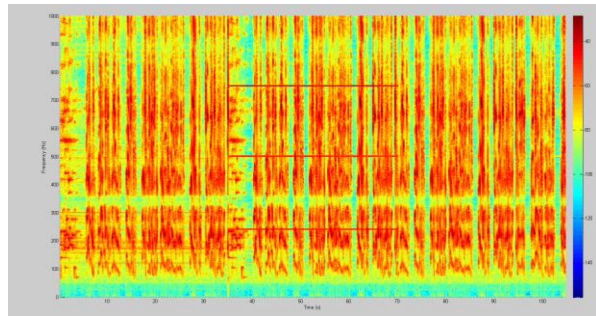

Fig.7. Spectrogram of HANC system (broadcast speech only at left part, broadcast both speech and noise when HANC is off, and broadcast speech and noise when HANC is on)

not affect the ANC performance and the ANC system does not cancel parents' voice as well

IV. CONCLUSION

This paper introduced wireless communication integrated multi-channel hybrid ANC system to cancel noises for infant incubators while boost bonding opportunities for the patients and their parents. The multi-channel hybrid ANC system was developed to cancel the incubator outside noise and the inside noise as well. The wireless communication integration subsystem was designed to provide two-way communication between infants and their caregivers. The real-time test bed set up was presented and used to evaluate the system's performance. The real-time experiments showed that the ANC system can dramatically reduce the noise and parent's speech quality can be improved as well.

ACKNOWLEDGMENT

This project is supported by NSF STTR grant (1448907).

REFERENCES

[1] Jeffrey Kluger, Preemie Revolution, 2014, Time Magazine, 24-31

[2] U. S. Department of Health and Human Services, 1992, Neonatal Intensive Care – A history of excellence, NIH Publication No. 92-2786.

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

[4] Lorenz, J.M., 2001, The outcome of extreme prematurity. Semin. Perinatol. 25: 348-359.

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

[6] Kenworthy, O. T., Bess, F.H., Stanhlman, M.T., and Lindstrom, D.P., 1987, Hearing, speech, and language outcome in infants with extreme immaturity, The American Journal of Otology, 8: 419-425.

[7] Trapanotto, M., Benini, F., Farina, M., Gobber, D., Magnavita, V., and Zacchello, F., 2004, Behavioural and physiological reactivity to noise in the newborn. J. Paediatr Child Health. 40: 275-281.

[8] Philbin, M. K., and Klaas, P., 2000, Hearing and behavioral responses to sound in full-term newborns. J. Perinatol. 20: S68-S76.

[9] Trapanotto, M., Benini, F., Farina, M., Gobber, D., Magnavita, V., and Zacchello, F., 2004, Behavioural and physiological reactivity to noise in the newborn. J. Paediatr Child Health. 40: 275-281.

[10] Saunders, J.C. and Chen, C.S. (1982) Sensitive periods of susceptibility to auditory trauma in mammals. Environ. Health Perspect. 44: 63-66.

[11] Birnholz, J.C. and Benacerraf, B.R.,1983, The development of human fetal hearing. Science 222: 516-518.

[12] Lary, S., Briassoulis, G., de Vries, L., Dubowitz, L.M. and Dubowitz, V., 1985, Hearing threshold in preterm and term infants by auditory brainstem response. J. Pediatr. 107: 593-599.

[13] American Academy of Pediatrics, Committee on Environmental Health, 1997, Noise: A hazard for the fetus and newborn, Pediatrics, 100: 724-727.

[14] Robertson, A., Cooper-Peel, C. and Vos, P., 1999, Sound transmission into incubators in the neonatal intensive care unit. J. Perinatol. 19:494-497.

[15] Carvalho, W. B., Pedreira M. L. G. and de Aguiar M. A. L., 2005, Noise level in a pediatric intensive care unit, Journal de Pediatria, 81: 495-498.

[16] W. D., Tan, A. K., Clarke, M. C., and Bardell, T., 2002, Excessive noise levels in the neonatal ICU: potential effects on auditory system development. J. Otolaryngol. 31:355-360.

[17] Philbin, M.K. and Evans, J.B., 2006, Standards for the acoustic environment of the newborn ICU. J. Perinatol. 26 Suppl. 3: S27-30.

[18] Nowicki, C. P., Mendat, D. P., and Smith, D. G., 1994, Active attenuation of motor/blow noise, Proc. Noise-Con, 415-420.

[19] Eghtesadi, K. and Ziegler, E., 1993, Frequency domain adaptive control algorithm for electric muffer application. Proc. Recent Advances in Active Control of Sound Vib., 574-585.

[20] Song, Y., Gong, Y., and Kuo, S. M., 2005, A Robust Hybrid Feedback Active Noise Cancellation Headset, IEEE Trans. On Speech and Audio Processing, 13: 607-617.

[21] S. Kuo and D. Morgan, “Active noise control: A tutorial review”, IEEE Proceeding, vol.87, no.6, pp. 943–973, 1999.

[22] Priya Thanigainayagam, Sen M. Kuo, and Ravi Yenduri, “Nonlinear Active Noise Control for Infant Incubators in Neo-Natal Intensive Care Units,” in Proc. IEEE ICASSP, April 2007, vol. I, pp.109-112.

[23] Priya Thanigainayagam and Sen M. Kuo, “Intrauterine Acoustics Embedded Active Noise Controller,” in Proc. IEEE Int. Conf. on Control Applications, Oct. 2007, pp. 1359-1364.

[24] L. Liu, S. Gujjula, P. T. Thanigainayagam, and S. M. Kuo, “Still in Womb: Interuterine Acoustic Embedded Active Noise Control for Infant Incubators,” Journal of Advances in Acoustics and Vibration, Special Issue on Active Noise Control, Vol. 2008, Article ID 495317, 9 pages, April 2008

[25] S. Kuo, L. Liu and S. Gujjula, ″Development and Application of Audio-Integrated ANC System for Infant Incubators, ″ Noise Control Engineering Journal, Vol. 58, No. 2, Mar-April 2010, pp 163-175

[26] Caskey, M., Stephens, B., Tucker, R. and Betty Vohr, Importance of Parent Talk on the Development of Preterm Infant Vocalizations, Pediatrics 2011;128;910; originally published online October 17, 2011;

[27] H. M. Obeidat, E. Bond and L. Callister, “The Parental Experience of Having an Infant in the Newborn Intensive Care Unit”, J Perinat Educ v.18(3); Summer 2009, pp. 23-29

[28] D. S. Lefkowitz, C. Baxt and J. R. Evans “Prevalence and Correlates of Posttraumatic Stress and Postpartum Depression in Parents of Infants in the Neonatal Intensive Care Unit (NICU)”, Journal of Clinical Psychology in Medical Settings September 2010, Volume 17, Issue 3, pp. 230-237

[29] S. Haykin, Adaptive Filter Theory (5th Edition), Pearson Education, Upper Saddle River, NJ, 2013

[30] L. Liu, B. Kapila and S. Kuo, “Multi-channel Hybrid Active Noise Control System for Infant Incubators”, 41st International Congress and Exposition on Noise Control Engineering, Volume 12, 2012, pp. 9806-9811.