CROSSTALK RESISTANT ADAPTIVE NOISE CANCELLATION APPLIED TO SOMATOSENSORY EVOKED POTENTIAL ENHANCEMENT

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ABSTRACT

Somatosensory Evoked Potentials (SEPs) are extremely useful in peripheral nerve monitoring and in the diagnosis of various neuromuscular disorders. However, surface measurements of these potentials often result in imperceptible SEP waveforms due to the very poor Signal-to-Noise Ratio (SNR). Adaptive noise cancelling is an attractive technique which can be used to improve this poor SNR. One of the important factors that affect the performance of an Adaptive Noise Canceller (ANC) is the presence of SEP components in the reference channel of the ANC. In this paper we propose a novel Multichannel Crosstalk Resistant Adaptive Noise Canceller (MCRANC) for offsetting the problems caused by the "SEP" crosstalk. The performance of this MCRANC is evaluated analytically and through simulations.

1. INTRODUCTION

Somatosensory Evoked Potentials (SEPs) are electrical signals emanating from the peripheral nervous system as a result of external stimulus [1]. The surface recorded SEPs suffer from poor SNRs, typically less than 0 dB and less than -10 dB in the presence of larger Myoelectric (muscle) Interference (MI) [1]. The Adaptive Noise Canceller (ANC) is an attractive solution for improving this very poor SNR. In its basic form, the ANC consists of a primary channel containing the SEP plus MI and a reference channel containing only a correlated component of the MI. The ANC acts as a correlation canceller thereby leaving interference free SEP at its output [2]. While this technique in its basic form is very appealing, its performance is affected by the presence of the SEP components in the reference channel, called the SEP "crosstalk", which results in undesirable SEP distortion [2,3]. A Crosstalk Resistant Adaptive Noise Canceller (CRANC), can be designed to offset the problems introduced by the SEP crosstalk [3,4]. The performance of this CRANC structure however is very sensitive to the presence of other uncorrelated noise sources [4]. In our application example of extracting SEP from MI, the uncorrelated noise emanates mainly from the recording apparatus and the primary and reference sensors. The uncorrelated noise power levels are often greater than the SEP and hence must be taken into consideration. In this paper we propose a Multichannel CRANC (MCRANC) structure which attempts to achieve the dual objectives of interference and crosstalk cancellation even in the presence of uncorrelated noise sources.

2. MCRANC FILTER STRUCTURE

The block diagram of the MCRANC in discrete Z domain is shown in Figure 1 where S(z) is the SEP, N(z) is the MI, H(z) is the MI transfer function, G(z) is the crosstalk transfer function, $U_1(z)$ and $U_2(z)$ are uncorrelated noise sources, and $W_1(z)$, $W_{21}(z)...W_{2M}(z)$ are the adaptive filters. Typically, in SEP measurement studies, the nerve is stimulated periodically to output an SEP train. The parameter "Δ" represents a delay of one stimulus period. Essential for the successful operation of this structure is to allow the first ANC to converge before the advent of the SEP *i.e.* before the nerve is stimulated. The Wiener solution of ANC #1 is then given by

$$W_1(z) = \frac{\phi_{NN}(z)H(z^{-1})}{\phi_{NN}(z)\,|H(z)|^2 + \phi_{U_2U_2}(z)} = \frac{1}{H(z)\{1+\tau_2(z)\}} \qquad (1)$$

where $\phi_{NN}(z)$ and $\phi_{U_2U_2}(z)$ represent the power spectral densities of N(z) and $U_2(z)$ respectively and $\tau_2(z)$ is the ratio of uncorrelated noise and MI spectral densities in the reference channel of ANC #1. Generally in the SEP measurements, $\tau_2(z)$ is less than 1 for all frequencies and therefore ANC #1 significantly reduces the MI. The Wiener solution of the second stage of the MCRANC is

$$[W(z)] = \begin{pmatrix} W_{21}(z) \\ W_{22}(z) \\ \cdot \\ W_{2M}(z) \end{pmatrix} \qquad (2)$$

and is given by the discrete Wiener - Hopf equation

$$[W(z)] = \left[\phi_{X_2X_2}(z)\right]^{-1}\left[\phi_{D_2X_2}(z)\right] \qquad (3)$$

where [ ] denotes a matrix, and $[\phi_{X_2X_2}(z)]$ is

$$\left[\phi_{X_2X_2}(z)\right] = \begin{pmatrix} \phi_{X_{21}X_{21}}(z) & \phi_{X_{21}X_{22}}(z) & \cdots & \phi_{X_{21}X_{2M}}(z) \\ \phi_{X_{22}X_{21}}(z) & \phi_{X_{22}X_{22}}(z) & \cdots & \phi_{X_{22}X_{2M}}(z) \\ \cdot & \cdot & \cdot & \cdot \\ \phi_{X_{2M}X_{21}}(z) & \phi_{X_{2M}X_{22}}(z) & \cdots & \phi_{X_{2M}X_{2M}}(z) \end{pmatrix}$$

and where $\phi_{X_{2i}X_{2j}}(z)$ is the cross spectral density between the ith and jth reference inputs of the second stage of MCRANC. The cross spectral density between the primary and reference inputs is $[\phi_{D_2X_2}(z)]$ which can be expressed as

$$\left[\phi_{D_2X_2}(z)\right] = \begin{pmatrix} \phi_{D_2X_{21}}(z) \\ \cdot \\ \cdot \\ \phi_{D_2X_{2M}}(z) \end{pmatrix} \qquad (5)$$

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Let

$$\phi_A(z) = \phi_{SS}(z)G(z)W_1(z)\{1 - G(z^{-1})W_1(z^{-1})\},$$

$$\phi_B(z) = \phi_{SS}(z)\,|\,1 - G(z)W_1(z)|^2, \text{and}$$

$$\phi_C(z) = \phi_{NN}(z)\,|\,1 - H(z)W_1(z)|^2 + \phi_{U_1U_1}(z) + \phi_{U_2U_2}(z)\,|\,W_1(z)|^2 \quad (6)$$

If we make the following reasonable assumptions:

1) The MI and the uncorrelated noise sources are wide sense ergodic processes,
2) The SEP repeats itself faithfully every Δ seconds, and
3) Both the MI and uncorrelated noise sources are uncorrelated with themselves after Δ seconds.

then,

$$[\phi_{X_2X_2}(z)] = \begin{pmatrix} \phi_B(z)+\phi_C(z) & \phi_B(z) & \cdots & \phi_B(z) \\ \phi_B(z) & \phi_B(z)+\phi_C(z) & \cdots & \phi_B(z) \\ \cdot & \cdot & \cdot & \cdot \\ \phi_B(z) & \phi_B(z) & \cdots & \phi_B(z)+\phi_C(z) \end{pmatrix}$$

and

$$[\phi_{D_2X_2}(z)] = \begin{pmatrix} \phi_A(z) \\ \phi_A(z) \\ \cdot \\ \phi_A(z) \end{pmatrix} \quad (8)$$

giving us the Wiener solution for the second stage of the MCRANC as

$$[W(z)] = \begin{pmatrix} \dfrac{\phi_A(z)}{M\phi_B(z)+\phi_C(z)} \\ \cdot \\ \cdot \\ \dfrac{\phi_A(z)}{M\phi_B(z)+\phi_C(z)} \end{pmatrix} \quad (9)$$

The output signal estimate can be easily calculated as,

$$\hat{S}(z) = S(z)\{1 - G(z)W_1(z)\}\{1 + MW_{21}(z)\} \quad (10)$$

Now,

$$1 + MW_{21}(z) = 1 + \frac{M\phi_A(z)}{M\phi_B(z)+\phi_C(z)} = 1 + \frac{\phi_A(z)}{\phi_B(z)+\frac{1}{M}\phi_C(z)} \quad (11)$$

and,

$$\lim_{M\to\infty} 1 + MW_{21}(z) = 1 + \frac{\phi_A(z)}{\phi_B(z)} = 1 + \frac{\phi_{SS}(z)G(z)W_1(z)\{1 - G(z^{-1})W_1(z^{-1})\}}{\phi_{SS}(z)\,|\,1 - G(z)W_1(z)|^2} = \frac{1}{1 - G(z)W_1(z)} \quad (12)$$

From Eqs 10 and 12, we can see that as the number of reference channels in the second stage of MCRANC tends to infinity, the SEP estimate at the output of the MCRANC approaches the undistorted input SEP.

The MI and uncorrelated noise components at the output of the MCRANC filter can be expressed as

$$\phi_{NNo}(z) = \phi_{NN}(z)\,|\,(1 - H(z)W_1(z))(1 + (1 + z^{-\Delta} + .. + z^{-(M-1)\Delta})(1 + W_{21}(z))|^2 \quad (13)$$

and

$$\phi_{UUo}(z) = \phi_{U_1U_1}(z)\,|\,1 + (1 + z^{-\Delta} + .. + z^{-(M-1)\Delta})W_{21}(z)|^2 + \phi_{U_2U_2}(z)\,|\,W_1(z) + (1 + z^{-\Delta} + .. + z^{-(M-1)\Delta})W_1(z)W_{21}(z)|^2 \quad (14)$$

As the number of channels tends to infinity, these can be expressed as

$$\phi_{NM}(z) = \lim_{M\to\infty} \phi_{NNo}(z) = \phi_{NN}(z)\,|\,1 - H(z)W_1(z)|^2$$

$$\phi_{UM}(z) = \lim_{M\to\infty} \phi_{UUo}(z) = \phi_{U_1U_1}(z) + \phi_{U_2U_2}(z)\,|\,W_1(z)|^2 \quad (15)$$

Let the input SNR be defined as $S_p^2/(\sigma_N^2 + \sigma_U^2)$ and the output SNR as $S_{po}^2/(\sigma_{No}^2 + \sigma_{Uo}^2)$, where S_p, σ_N^2, and σ_U^2 are the SEP peak amplitude, MI and uncorrelated noise variances respectively and S_{po}, σ_{No}^2, and σ_{Uo}^2 are the corresponding values at the output of the MCRANC. The SNRGAIN, γ, has an upper limit as the number of reference channels tends to infinity which is given by

$$\gamma_{max} = \frac{\int \phi_{NN}(z)dz + \int \phi_{UU}(z)dz}{\int \phi_{NM}(z)dz + \int \phi_{UM}(z)dz} \quad (16)$$

with the integrals evaluated on the unit circle in Z domain. Thus, as the number of reference channels in the second stage of MCRANC is increased, the SNRGAIN increases until it reaches the maximum value and the signal distortion decreases regardless of the amount of signal crosstalk and even in the presence of uncorrelated noise sources. This point is clearly depicted in the theoretical performance surfaces of the MCRANC filter, in terms of the SNRGAIN and the distortion index, shown in Figures 2 and 3.

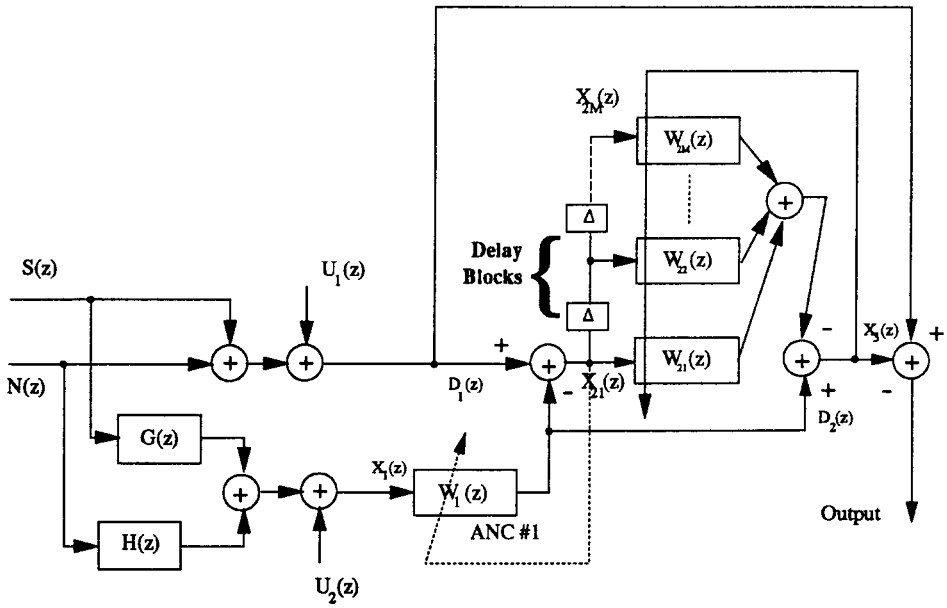

Figure 1: *Block Diagram of the MCRANC Filter.*

3. SIMULATION

The MI interference is simulated by passing unit variance Gaussian white noise through a first order low pass filter. The uncorrelated noises are white Gaussian noise sources. The SEP is generated using the following equation,

$$s(n) = K_1 nT(2 - C_1 nT)e^{-C_1 nT} \tag{13}$$

where K1 is a scaling factor, C_1 is the bandwidth constant typically equal to 2500 for the SEP signal, n is the time index and T is the sampling period. In order to reflect physiological conditions, H(z) is modeled as a low pass filter given by $H(z) = A/(1+\alpha z^{-1})$ where A is a constant and α is the filter coefficient. For the sake of simplicity, G(z) is made equal to a constant, $\beta < 1$. The ratio σ_U^2/σ_N^2 was set to 0.001. Twenty tap FIR filters driven by RLS algorithm are used to realize the adaptive filters in the first and second stages of the MCRANC. Fifty independent simulation runs are performed, and the steady state adaptive filter weights at the end of each simulation run are averaged. These averaged filter weights are then used to filter the SEP, MI and uncorrelated noise separately to obtain their estimates at the output. Two different measures are used to assess the performance of the MCRANC *viz* the distortion index which is a normalized mean squared error measure between the output SEP estimate and the input SEP, and the SNRGAIN. Figure 4a-b depict these performance measures for two different crosstalk values for an input SNR of 0.025. The corresponding theoretical values were computed by first calculating the Wiener solutions given by Eqs. 2 and 9 using input spectral information, computing the output signal and noise estimates next and then calculating the distortion index and the SNRGAIN. It is obvious from these plots that an increase in the number of reference channels results in a decreasing distortion index and an increasing SNRGAIN. A good agreement between the theoretical and simulation results can be seen and the differences are mainly due to the convergence properties of the adaptive filters.

4. CONCLUSION

SEPs are clinically valuable biological signals whose surface recordings suffer from poor SNR. In this paper we explored a novel Multichannel Crosstalk Resistant Adaptive Noise Canceller (MCRANC) for SEP enhancement. The MCRANC consists of two stages: stage #1 for reducing the MI and stage #2 for compensating the signal crosstalk. It is shown that the MCRANC structure outputs an SEP, whose distortion decreases and SNR increases as the number of reference channels in the second stage increases.

5. REFERENCES

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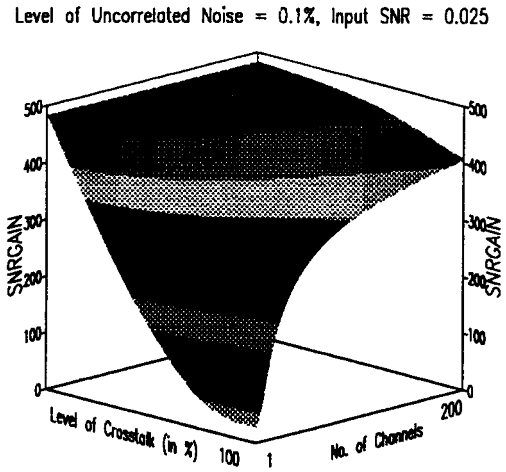

Fig. 2: *Theoretical SNRGAIN by MCRANC.*

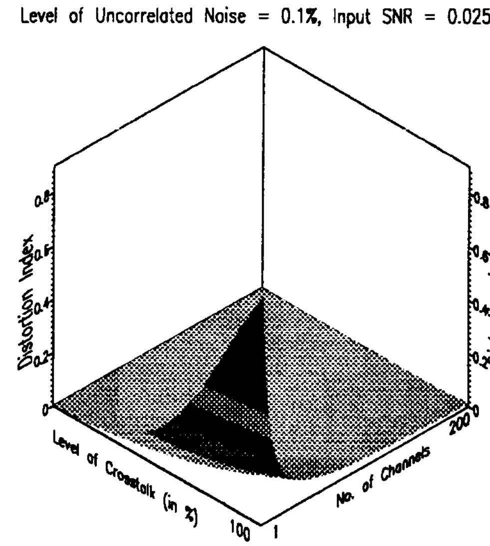

Fig. 3: *Theoretical Distortion Index by MCRANC*

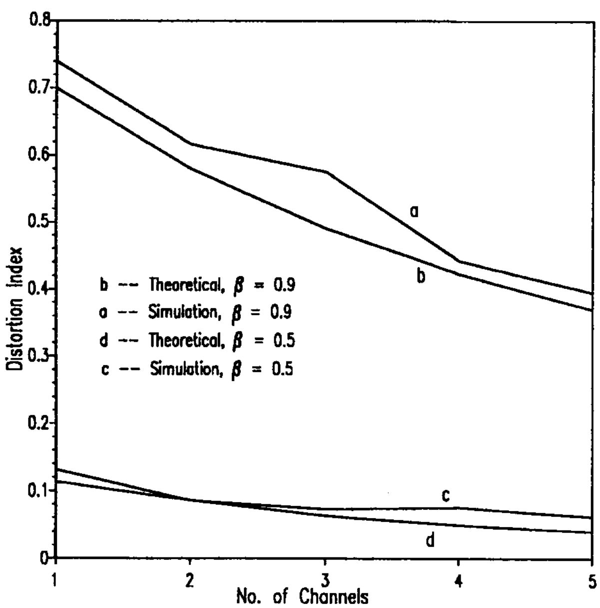

Fig. 4a: *Distortion Index Vs No. of Channels*

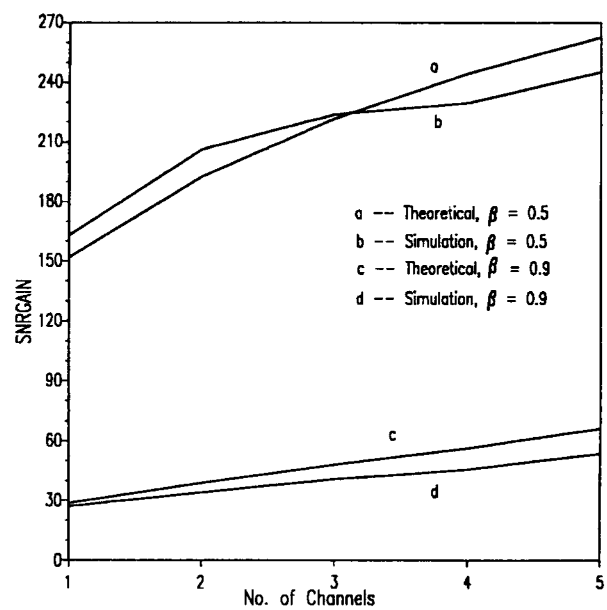

Fig. 4b: *SNRGAIN vs No. of Channels*