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Electroencephalographic Signal Enhancement Using Nuttall-Welch Hybrid Window

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***Abstract*—Windows are essential working tool in the design of digital finite impulse response (FIR) filters. They are also used in the design of antenna and beamforming.Windows also are applied in spectral and statistical analysis, spectral modification and spectral re-synthesis. A window is a mathematical function that has definite sample duration. That means its origination and termination are definite and time bound. Windows'response to the length of any input signal is to truncate the input response to definite impulse response. The windowing process is applied a spectral data or statistical data by multiplying a window function with the desired unit sample response of the data. In this paper, a new window is proposed.The new window is a hybrid of Nuttall and Welch windows called Nuttall-WelchHybrid (NWH) Window. The window is applied in the modeling of FIR filter for the reduction of 50Hz power line interference (PLI) from electroencephalographic (EEG) signal.**

***Index Terms*—EEG, FIR filter, Hybrid window, Nuttall window, Welch window**

I. INTRODUCTION

In finite impulse response (FIR) digital filter design, window is used to formulate the unit sample response of the FIR filter. Many windows in their original state have been used in this process including modified windows. Some of the modified windows used in FIR filter designs are Height Adjustable Triangular (HAT) Window and Height Adjustable Sine (HAS) Window [1][2].More research works are now on-going in modifying window functions for the purpose of FIR filter design. Hybrid window concept is another dimension of window modification. This concept is entirely a new innovation as not much work is done in this aspect. In [3] Jaya et al used a combination of Blackman and Kaiser Windows to form a hybrid window with which the researchers used in modeling an FIR digital filter. The era of hybrid window is evolving, and there is no doubt that this area calls for more research work.

In this work, a new hybrid window is proposed. A duo of Nuttall and Welch Windows are combined with multiplication operator. The proposed window is used in 50Hz power line interference (PLI) reduction from electroencephalographic (EEG) signal. However, 50Hz PLI removal from EEG has been demonstrated in the time past using Nuttall and Welch Windows individually as well as in other applications. This can be seen in [4][5][6][7].

EEG is a brain generated electrical signal. It is very important in the diagnosis of brain related illnesses. The effective and efficient usefulness of any recorded EEG signal by the clinicians will have to face heavy jeopardy if the signal is corrupt with other signals.Some other electric waves are actually traceable to the scalp and can be picked alongside EEG signal in the process of recording EEG.These other signals are unwanted signals and can be referred to as noise. Electrocardiogram (ECG), electromyogram (EMG), and electro-oculogram (EOG) as well aspower line interference (PLI) and Baseline Wanders (BW) are the noises that can berecorded with EEG in the process of obtaining EEG from the patient. The proposed hybrid window is used to demonstrate the ability of FIR filters in EEG signal enhancement by removing50Hz PLI from EEG.

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II. PROPOSED NUTTALL-WELCH HYBRID WINDOW

A new window called the Nuttall-Welch Hybrid (NWH) Window is proposed. NWH Window is formulated by combining the Nuttall and Welch Windows with a multiplication operator. The mathematical functions of the Nuttall Window $w_1(n)$ and Welch Window $w_2(n)$ are given in (1) and (2) respectively.

$$w_1(n) = a_0 - a_1\cos(\frac{2n\pi}{N-1}) + a_2\cos(\frac{4n\pi}{N-1}) - a_3\cos(\frac{6n\pi}{N-1}) \quad (1)$$

Where a_0 = 0.355768; a_1 = 0.487396; a_2 = 0.144232; a_3 = 0.012604, N is length of samples.

$$w_2(n) = 1 - (\frac{n - \frac{N-1}{2}}{\frac{N-1}{2}})^2 \quad (2)$$

Note to achieve a unity peak, both component windows shall have even window filter order. This means that L shall be even and window length N shall be odd. This will also produce an even L. The mathematical function of the NWH Window is obtained by multiplying (1) by (2) to form (3) as shown below.

$$w(n) = w_1(n) * w_2(n) \quad (3)$$

Applying (3), the mathematical expression of the NWH Window in MATLAB environment givesthe amplitude and magnitude responses of the new window as displayed in fig 1 and fig 4 intime domain and frequency domain of the new window respectively. Fig 2 and fig 3 show the time domain responses of the Nuttall and the Welch Windows in that order. The magnitude responses of Nuttall Window and Welch Windoware shown in fig 5 and fig 6 respectively.From the graphical representations of the magnitude responses the three windows, it can be deduced that the newly proposed hybrid window has a better main lobe - side lobe difference. The phase response of the NWH Window is shown in fig 7. The phase response shows that the window is linear. Importantly,good linearity property of a window shows that the window will make a stable and very good filter when implemented in FIR digital filter modeling.Linearity and the subsequent stability are very important tools in FIR filter modeling.

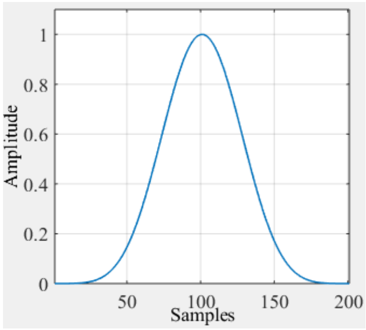

Fig 1; NWH Window plot in Time domain

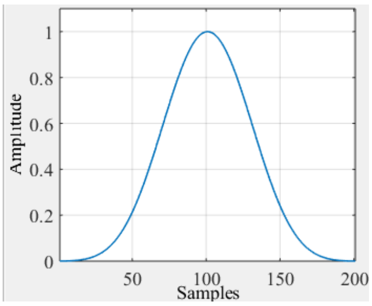

Fig 2; Nuttall Window plot in Time domain

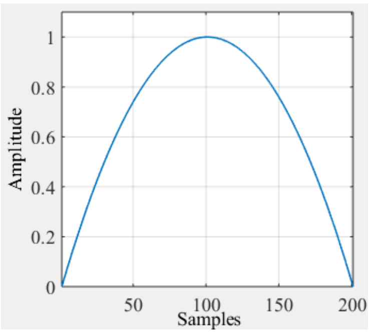

Fig 3; Welch Window plot in Time domain

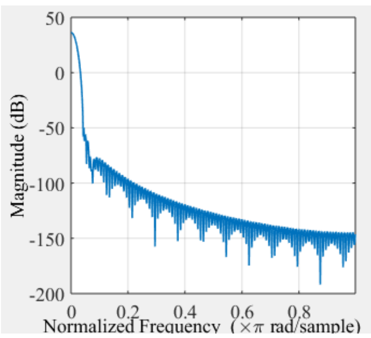

Fig 4; NWH Window plot in Frequency domain

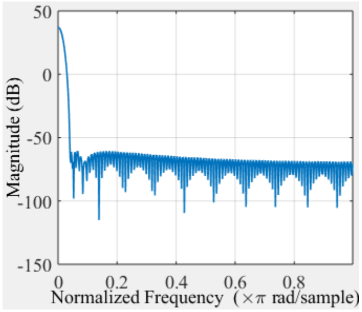

Fig 5; Nuttall Window plot in Frequency domain

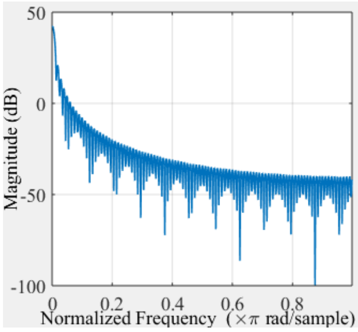

Fig 6; Welch Window plot in Frequency domain

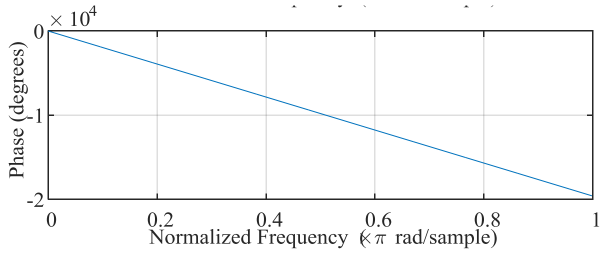

Fig 7; Phase response of NWH Window

III. Filter Design And Implementation

With the aid of MATLAB application, the newly proposed window is designed and implemented. The NHW Window is used to enhance a real EEG signal acquired from a female patient by reducing 50Hz 5mV PLI from the signal.The process of FIR filter modeling starts by using a chosen window to truncate the desired unit sample response $h_d(n)$ ofinfinite filter response to create a finite filter response. This is achieved by multiplying the desired unit sample response $h_d(n)$ by the window function (W_n). This procedure is referred to aswindowing. The product windowing is known as the unit sample response of an FIR filter h(n). The mathematical expression of windowing is shown in (4).

$$h(n) = h_d(n) * w(n) \quad (4)$$

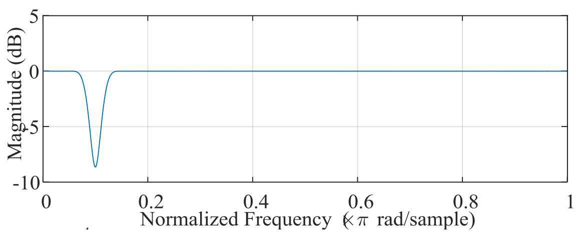

Fig 8; Magnitude response of Nuttall-Welch Hybrid notch filter

More so, fig 8 shows Magnitude response decibel (dB) of NWH notch filter. Having designed the NWH-Windowed FIR filter, the implementation of the filter is simulated in using MATLAB application. Firstly, EEG signal is introduced into the MATLAB environment (EEG is shown in fig 9. Secondly, 50Hz 5mV amplitude PLI is generated using the application. 50Hz 5mV PLI is shown in fig 10. Then MATLAB commands are used to implement a signal mixture of EEG and PLI to form a contaminated EEG signal. Contaminated EEG is shown in fig 11. At this point, the NWH-Windowed FIR filter is applied on the contaminated EEG and a signal very close in resemblance to the original EEG is obtained. This is the filtered EEG as shown in fig 12. This result is evident that the proposed NWH-Windowed FIR filter has successfully enhanced the noisy EEG.

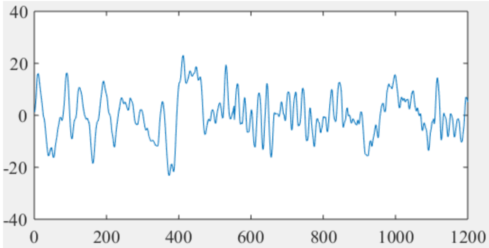

Fig 9; EEG signal

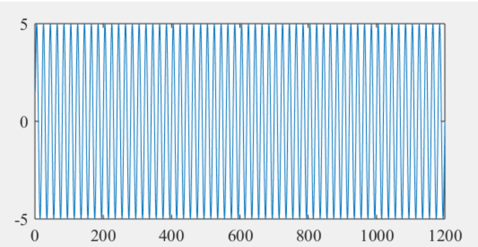

Fig 10; 50Hz PLI

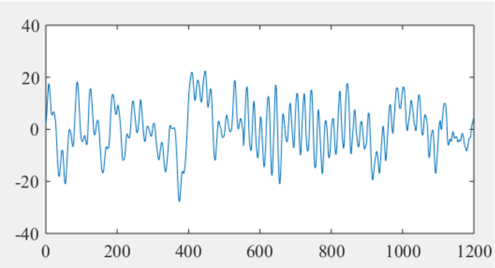

Fig 11; Contaminated EEG

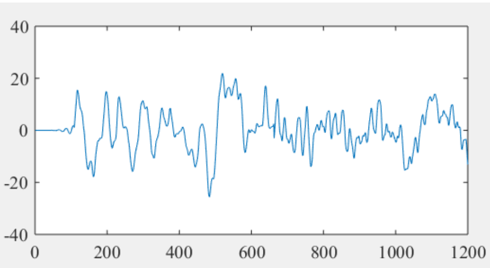

Fig 12; Filter EEG

This demonstrates good signal enhancement property for the new filter. NWH Window and NWH–windowed FIR filter parameters of the new filter are as follow;

- Filter type; Band stop filter
- Upper limit frequency; 55Hz
- Lower limit frequency; 45Hz
- Sampling frequency; 1000Hz
- Filter order 217

IV. Result Analysis

Two methods of analysis will be used to analyze the performance of the NWH-Windowed FIR filter. The analytical methods are Magnitude Response Estimate (MRE) and Power Spectral Density Estimate (PSDE).These two analytical systems are individually applied on four important signals that make up the basic analytical tools of this work. The four signals are thus; EEG, 50Hz PLI, EEG corrupted with PLI and filtered EEG. The effect of these four signals will be evaluated using the MRE and PSDE.

A. Result Analysis Using Magnitude Response Estimate

The capability and effectiveness of the proposed NWH-Windowed FIR filter in EEG signal enhancement can be evaluated with MATLAB's MRE. Firstly, from fig 8, it can be noticed that the magnitude response of the system occurs at the normalized frequency value of 0.1π rad/sample. So the analysis of the EEG, 50Hz PLI, EEG corrupted with PLI and filtered EEG will be evaluated at the same point of 0.1π rad/sample. In fig 13, it can be seen that the MRE of the original EEG at normalized frequency value of approximately 0.1π rad/sample is 62.3381dB. Please note that the pick value is been considered. In the same vein, MRE value of the 50Hz PLI in fig 14 at normalized frequency value of approximately 0.1π rad/sample is 68.5746dB. Then, when the two signals; EEG and PLI are added together to form EEG-PLI corrupted signal, the MRE value of the signal at the same point of 0.1π rad/sample of normalized frequency is observed to have risen to 69.7676dB. The MRE plot for the noisy EEG is shown in fig 15.

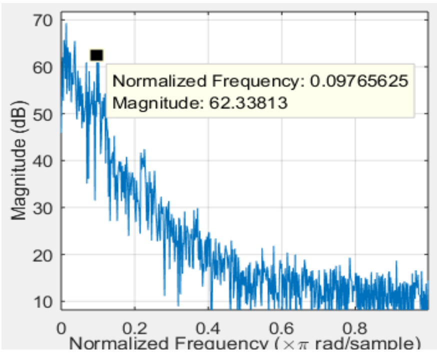

Fig 13;MRE plot of EEG

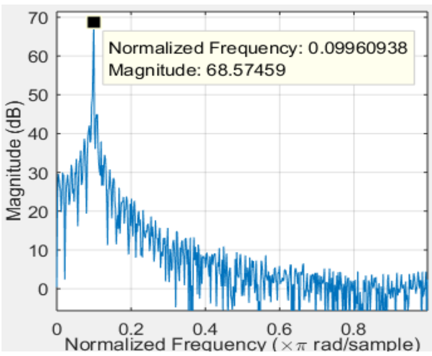

Fig 14;MRE plot of 50Hz PLI

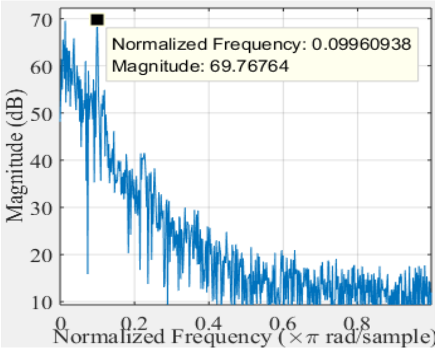

Fig 15;MRE plot of noisy EEG

Evantually, when the artifact affected EEG is applied to the proposed NWH-Windowed FIR filter, signal filtration effect can be noticed. The filter outputs filtered EEG. This is shown in fig 16. Evaluating the MRE plot of the filtered EEG shows that at the same normalized frequency value of approximately 0.1π rad/sample, the MRE value has become 62.2003dB. This MRE value is comparable to the MRE value of the original EEG in fig 13.

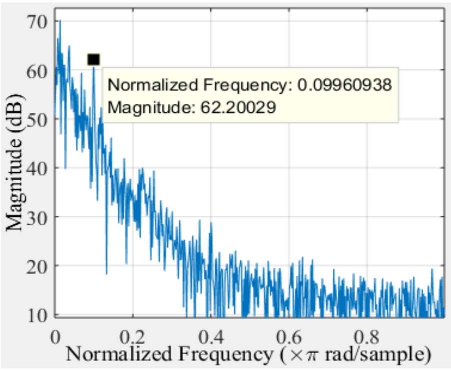

Fig 16; MRE plot of Filtered EEG

However, the MRE value of 62.2003dB for the filtered EEG was obtained using filter order 200 and window length 201. This means that the best filter order for the proposed window in EEG signal enhancement is 200. Interestingly, several values were tested for filter order in the work. But the researchers eventually settle for the value 200 having given the best output. That is the closest MRE to that of the original MRE. Table 1 showsvarious filter orders used and their corresponding window length as well as their corresponding MRE.

Table 1; Filter order with corresponding window length and Magnitude Response Estimate values of filtered EEG

Filter Order	Window length	Magnitude Response Estimate (dB)
180	181	63.1784
190	191	61.9905
200	201	62.2003
202	203	62.0513
204	205	61.6963
206	207	62.0982
208	209	60.8261
210	211	61.1879
212	213	61.3688
214	215	61.0267
216	217	60.7137
218	219	60.7937

B. Result Analysis Using Power Spectral Density Estimate

The second analytical method employed in this work is the Power Spectral Density Estimate (PSDE). Once more, the four signals of this research work are plotted and analyzed with PSDE. EEGsignal and PLI signal for PSDE are plotted in fig 17 and fig 18 respectively.The positions of the spikes representing both the EEG and PLI can be noted. In fig 19 is shown the EEG-PLI contaminated signal. The plot representing the noisy EEG, the spikes that appeared in fig 17 and fig 18 can be seen to be well represented for EEG and PLI combined together.Interestingly, when the contaminated EEG is filtered with the proposed NWH-Windowed FIR filter, a plot representing the filtered EEG is obtained as shown in fig 20. The plot in fig 17 representing original EEG and the one in fig 20 representing filtered EEG have the same look. In the plot representing filtered EEG, it can be shown that the PLI spike that appeared in fig 19 has been removed by the proposed filter.This has demonstrated that the proposed NWH-Windowed FIR filter can effectively implement FIR filter application in digital signal processing.

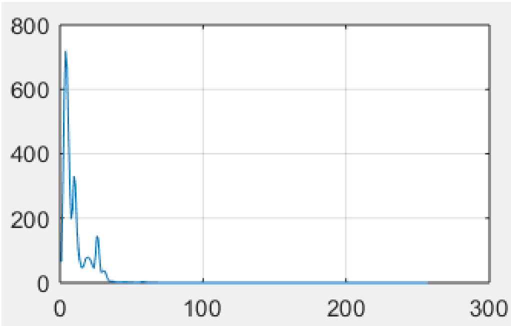

Fig 17 PSDE of EEG signal

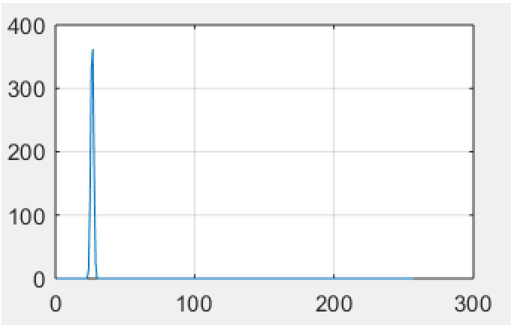

Fig 18 PSDE of 50Hz PLI

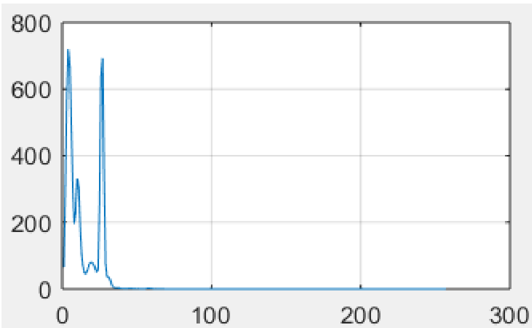

Fig 19 PSDE of contaminated ECG signal

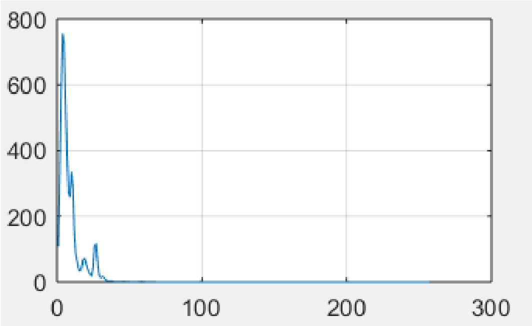

Fig 20 PSDE of filtered EEG signal

V. Conclusion

Two windows namely Nuttall Window and Welch Window have been used to develop a hybrid window called the Nuttall-Welch Hybrid (NWH) Window. Mathematical operator employed in the hybrid formation is multiplier operator. NWH Window was used to perform 50Hz PLI reduction from contaminated EEG. This work further demonstrates that hybrid window is effective in modeling FIR filters for EEG signal enhancement. The NWH Window presents a good linearity property and in turn formed a stable FIR filter.

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