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EEG Signal Improvement; Comparison of Different Windows

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Abstract—**Clinical information of the brain is used for analysis, diagnosis and treatment of brain related ailments. The information from the brain is obtained through an electronic device known as the Electroencephalograph. This device reads, records and graphically displays the electrical potentials of the brain of the patient for proper clinical attention from the clinicians. The electrical potential of the brain is called electroencephalogram (EEG). The process of collecting EEG signal involves the placement of electrodes (probes) of Electroencephalograph on the patient's scalp. It is important to note that the scalp shall be properly shaved for a very good probe-scalp contact. However, all electrical signals travelling on the scalp are picked by the Electroencephalograph. The eye, muscle and heart all generate electrical signals that are traceable to the scalp. All these signals are recorded alongside with the EEG and they constitute a list of unwanted signals or noise to EEG. They compromise the information contained in the recorded EEG and simply make it very difficult for the physicians to affectively use the EEG. Power line interference (PLI) is another signal that corrupts EEG. The presence of any of these unwanted electrical potentials in the recorded EEG is undesirable. Hence proper diagnosis and interpretation are achievable when the noise is removed from the recorded EEG before the signal is displayed. Moreover, this paper compares finite impulse response (FIR) filters modeled with different windows for the purpose of removing 50Hz power line interference from EEG. The FIR filter technique employed, involves the use of ten different windows namely; Kaiser, Parzen, Gaussian, Hann, Hamming, Rectangular, Nuttall, Blackman Harris, Welch and Height Adjustable Sine (HAS) Windows. Effort is made to ascertain the effectiveness of each of the ten FIR filters PLI interference reduction by comparing the mean squared error (MSE) of the filters designed with each of the ten windows. It was concluded that the Hamming Window made the best MSE seconded by the Hann Window.**

Index Terms— **EEG signal, FIR filter, Mean squared error, Noise reduction, , Windows.**

I. INTRODUCTION

The brain is capable of discharging some electrical potential known as electroencephalogram (EEG). The information represented in EEG is very vital as they are used in diagnosis, analysis and treatment of neural disorder and other brain related diseases [1][2]. Other biologically generated electrical signals around the head tend to contaminate the EEG signal as it is being obtained from the scalp of the subject [3]. These contaminants are Electrooculogram (EOG), Electrocardiogram (ECG), Electromyogram (EMG) and 50/60Hz power line (PLI) interference introduced by the EEG instrument. However, EOG is electrical potential that originates from the eye. EOG is discharged when the eye blinks or its retina moves. This can be easily picked by the EEG probes due to the proximity of the eye to scalp. In the same vein, the vascular system transports ECG to the human head and so does the muscular system conveying EMG to the head. Some of the electronic components used in designing the EEG device produce 50/60Hz power line interference. This can be referred to as the capacitive-inductive coupling effect of the circuits of the EEG device. Presence of artifacts in EEG poses a huge difficulty in EEG signal analysis and should be removed to make the signal usable. This paper compares the effectiveness of finite impulse response (FIR) windowed filters of ten different windows in 50Hz power line noise reduction by checking on their MSE. The windows used are Kaiser, Parzen, Gaussian, Hann, Hamming, Rectangular, Nuttall, Blackman Harris, Welch and Height Adjustable Sine (HAS) windows.

A lot of works have been done in comparing the effectiveness of different window-based FIR filters in artifacts attenuation from biological signals. The effectiveness of six different window functions in modeling FIR notch filter was been carried out in [4]. The researcher used the FIR filters produced with the six windows to reduce 50Hz power line interference from ECG. The windows used are Kaiser, Hanning, Hamming and Blackmann Windows as well as Height adjustable sine Window (HAS) and Height adjustable triangular (HAT) Window. Both the HAS Window [5] and HAT Window [6] are windows formulated by the researchers. It was found out that, out of the six windows, Kaiser Window yielded the best result in terms of SNR followed by HAS Window. Secondly, another comparison of FIR filters was made involving Gaussian, Bartlet and Hann Windows in removing PLI from ECG [7]. In the work, the researcher showed that Gaussian Window gave the best SNR performance followed by the Hann Window leaving Bartlet Window with the least SNR value. Furthermore, in the third review, a work on three high pass FIR window-based filters involving Nuttall, Parzen and Rectangular Windows was also executed [8]. The researchers summarized the result of their findings by stating that Nuttall window produced the best main lobe and relative side lobe attenuation while Parzen Window ranked second among the three windows. Fourthly, FIR filter implemented on C6713 DSK using six different window techniques for ECG noise reduction was modeled using Rectangular, Kaiser, Hanning, Hamming, Blackman and Bartlett Windows [9]. The researchers showed that Hanning Window gave the best SNR out of the six windows considered, followed by Kaiser Window. More so, the researchers in the fifth review [10], after ECG signal de-noising analysis using Kaiser, Rectangular, Hanning, Hamming and Blackman windows concluded that with higher filter order Hamming Window followed by

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Rectangular Window gave the best SNR. While Kaiser Window followed by Hanning Window gave the better mean squared error (MSE) than others. Lastly, Kaiser Window followed by Blackman Harris window was preferred over Gaussian and Blackman windows in a performance analysis of power line interference removal from ECG according to [11].

This work seeks to compare the performance of top two windows from each of the six research publications reviewed. The windows are; Kaiser, Parzen, Gaussian, Hann, Hamming, Rectangular, Nuttall, Blackman Harris, Welch and HAS Windows. The FIR filters modeled with each of the windows is applied to 50Hz PLI corrupted EEG signal to enhance the signal and to determine the window that yields the best MSE.

II. WINDOW FEATURES

In FIR filter modeling, window is a very important tool in the art. Windows are used to truncate the infinite response of the desired unit sample response $h_d(n)$ to a definite limits, thereby making the desired unit sample response a finite impulse response. Some window sequence generally originates from zero, rises to unity or modified pick and falls back zero in a symmetrical form. The following windows are used in this work. They are Kaiser, Parzen, Gaussian, Hann, Hamming, Rectangular, Nuttall, Blackman Harris, Welch and HAS Windows. These windows can be represented with mathematical expressions. MATLAB’s Window Design and Analysis Tool ‘wintool’ is used to display various some properties of these windows graphically.

A. Kaiser Window

The mathematical expression of Kaiser Window is shown in equ 1. Time domain and frequency domain plots of the window are displayed in fig 1. Filter parameters used for the Kaiser plots in fig 1 are as follows; filter order L = 100, in line with the filter order used in the work in [12]. Beta β = 7. In [12] the researchers recommended that the range of β shall be between 4 < β <9, but in this work, β = 7 is used.

$$W(n) = I_0\left(\frac{\pi\alpha\sqrt{1-(\frac{2n}{N-1}-1)^2}}{I_0(\pi\alpha)}\right) \qquad \text{Equ 1}$$

Where I_0 is the zero-order modified Bessel function of the first kind and N is the window length. α is the non-negative real number that determines the shape of the window. In the frequency domain, α also determines the trade-off between main-lobe width and side lobe level, which is a central decision element in window design.

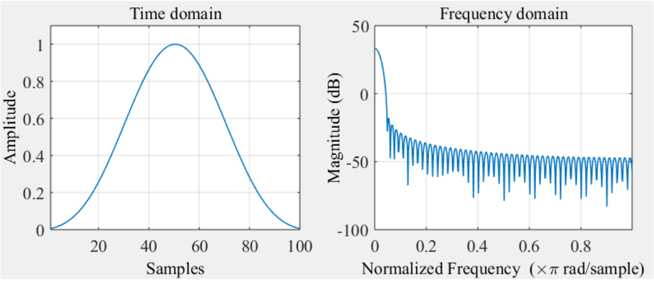

Fig 1: Time domains and frequency domain plots of Kaiser Window for N = 100, β = 7.

B. Parzen Window

Equ 2 shows the mathematical function for the Parzen Window. Fig 2 displays the time domain and the frequency domain plots of Parzen Window for filter Order 100 samples. Interestingly, in [13] the same filter order of 100 is used.

$$W(n) = \begin{cases} 1-6\left(\frac{n}{N/2}\right)^2\left(1-\frac{|n|}{N/2}\right) for 0 \le |n| \le (N/4) \\ 2\left(1-\frac{|n|}{N/2}\right)^3 for (N/4) \le |n| \le (N/2) \end{cases} \qquad \text{Equ 2}$$

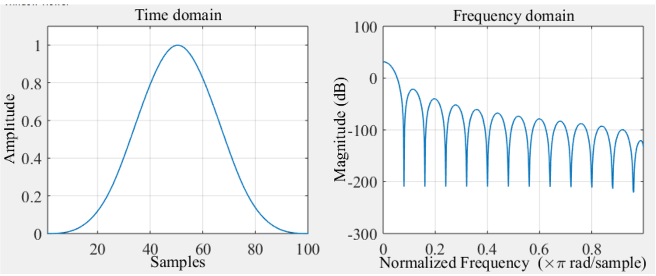

Fig 2: Time domain and frequency domain plots of Parzen Window.

C. Gaussian Window

Standard deviation σ is a very vital parameter for Gaussian Window. As the σ increases, the window gets wider. This makes the truncation to become more severe. In other words, the higher the σ, the better the frequency response of the filter [7]. Gaussian Window function is calculated by the function in equ 3. Meanwhile, fig 3 displays the time domain and the frequency domain plots of the Gaussian Window for filter order equals 100. The value of α varies with the shape of the window. However, in this work α is taken to be equal to 3.

$$W(n) = e^{-0.5\left(\frac{n-(N-1)/2}{\sigma(N-1)/2}\right)^2} \qquad \text{Equ 3}$$

Where σ = 0.5

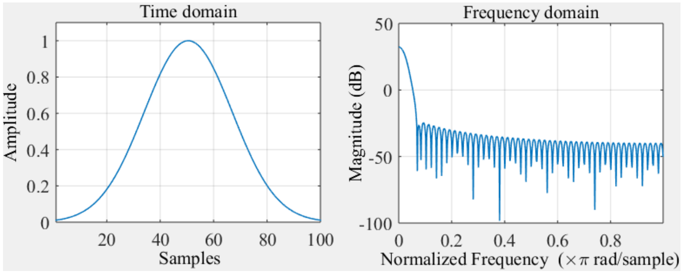

Fig 3: Time domain and frequency domain plots of Gaussian window for L = 100, α = 3.

D. Hann Window

The Hann Window is named after Austria meteorologist, Julius Ferdinand von Hann [14]. It is sometimes referred to as Hanning Window. This window is described as a raised cosine function. It is mathematically represented as expressed in equ 4. The time domain and the frequency domain plots of Hann Window for filter order 100 is shown in fig 4.

$$W(n) = 0.5\left(1 - \cos\left(\frac{2\pi n}{N-1}\right)\right) = \sin^2\left(\frac{\pi n}{N-1}\right) \quad \text{Equ 4}$$

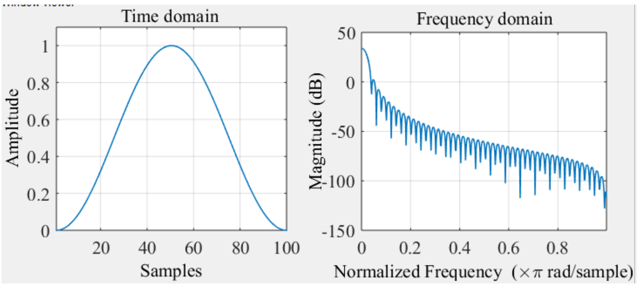

Fig 4: Time domain and frequency domain plots of Hann window for L = 100.

E. Hamming Window

The Hamming window is one of the most widely used windows in digital signal processing (DSP). It is believed to be a modified Hann Window [14]. It can be seen that the spectral windows of both Hamming and Hann Windows are summations of three-shifted kernels [14]. However, the mathematical expression for the Hamming Window is shown in equ 5.

$$W(n) = \alpha - \beta\cos\left(\frac{2\pi n}{N-1}\right) \qquad \text{Equ 5}$$

Where α = 0.54, β = 1 – α

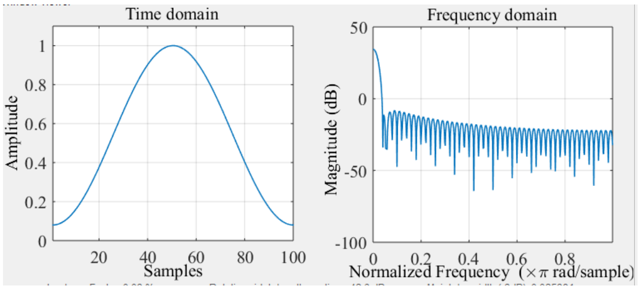

Fig 5: Time domain and frequency domain plots of Hamming window for L = 100.

F. Rectangular Window

This window has the simplest mathematical function as can be seen in equ 6. It is a static magnitude window having all its samples at unity. The time and the frequency domains plots for the Rectangular Window are displayed in fig 6. The window length used to plot fig 6 is 101, otherwise L is equal to 100.

$W(n) = 1$, Equ 6
For $|n| < M$ (otherwise zero)

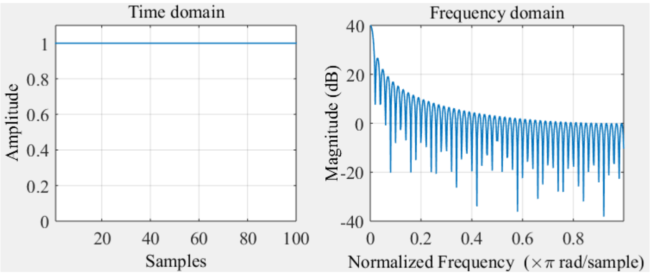

Fig 6: Time domain and frequency domain plots of Rectangular Window for length 100.

G. Nuttall Window

Mathematical expression of Nuttall Window is shown in equ 7. Meanwhile the time domain and the frequency domain plots of the window are shown in fig 7 of Nuttall window for filter order is 100.

$$W(n) = a_0 - a_1\cos\left(\frac{2\pi n}{N-1}\right) + a_2\cos\left(\frac{4\pi n}{N-1}\right) - a_3\cos\left(\frac{6\pi n}{N-1}\right) \quad \text{Equ 7}$$

Where $a_0 = 0.355768$, $a_1 = 0.487396$, $a_2 = 0.144232$, $a_3 = 0.012604$

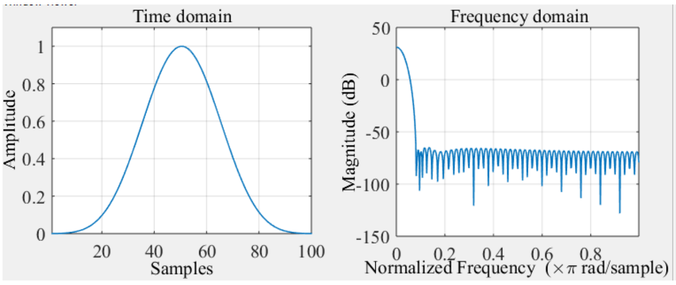

Fig 7: Time domain and frequency domain plots of Nuttall Window.

H. Blackman Harris Window

The Blackman Harris Window is in the same family with the Nuttall Window. The major difference between this window and the Nuttall Window is in values of their coefficients. The function Blackman Harris Window is given in Equ. 8 while fig 8 shows its time domain and the frequency domain plots for filter order L= 100.

$$W(n) = a_0 - a_1\cos\left(\frac{2\pi n}{N-1}\right) + a_2\cos\left(\frac{4\pi n}{N-1}\right) - a_3\cos\left(\frac{6\pi n}{N-1}\right) \quad \text{Equ 8}$$

Where $a_0 = 0.35875$, $a_1 = 0.48829$, $a_2 = 0.14128$, $a_3 = 0.01168$

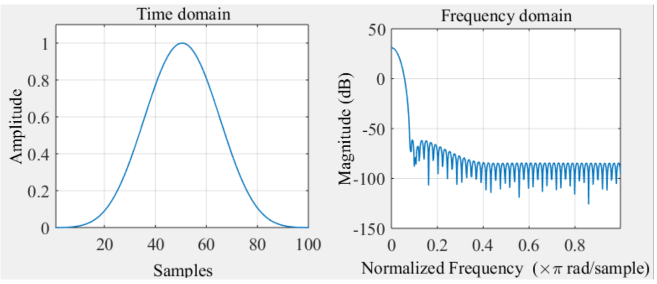

Fig 8: Time domain and frequency domain plots of Blackman Harris Window for L = 100.

I. Welch window

The Welch Window has been demonstrated to be effective in FIR windowed-filter model in EEG-PLI noise reduction [15]. Filter order of the Welch Window used in the PLI reduction from EEG is 100. Due to the effectiveness of the window, the researchers wish to include the window in the list of windows for comparison. Equ. 9 shows the function of Welch Window and fig 9 shows the time domain and the frequency domain plots for Welch Window of filter order L = 100.

$$W(n)=1-\left(\frac{n-\frac{N-1}{2}}{\frac{N-1}{2}}\right)^{2} \qquad \text{Equ 9}$$

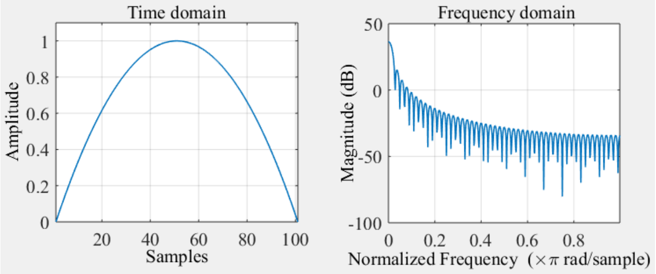

Fig 9: Time domain and frequency domain plots of Welch Window for L = 100.

J. *Height Adjustable Sine (HAS) Window*

The Height Adjustable Sine (HAS) Window is a modification of the Sine Window [16] in which the origin can be made to start from any point zero to 1. Equ 10 shows the expression for the HAS Window.

$$W(n)=\begin{cases}\alpha+\sin\left(\frac{2\sin^{-1}}{N}(1-\alpha)\right)n, & 0\le n\le\frac{N-1}{2}\\ \alpha+\sin\left(\left(\frac{(N-n)2\sin^{-1}}{N}\right)(1-\alpha)\right)n, & \frac{N-1}{2}\le n\le N-1\end{cases} \qquad \text{Equ 10}$$

The symbol ‘α’ represents the window adjustment parameter which can vary from 0 to 1. Ideally the value of α shall be kept as low as possible for a realistic filter application. In this work α is equal to 0.07.

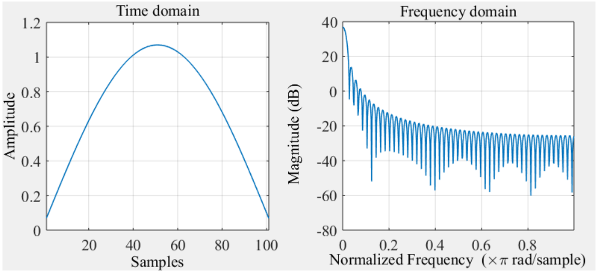

Fig 10: Time domain and frequency domain plots of HAS for L = 100, α = 0.07.

In this work, the researchers shall modeled windowed FIR filters using each of the ten windows highlighted earlier. Although the windows are chosen out of the two top windows in the reviewed research works in addition to the Welch window. The chosen windows as reviewed were modeled with certain filter orders in those works with which they made the tops in filtration, MSE and SNR marks. More so, some of these windows in the review works were used on ECG, hence the researchers deem it fit to use almost a common filter order for all the ten windows as considered convenient. However, this work models FIR filters with the chosen windows for EEG signal enhancement with filter order 100, 120 and 140.

Important filter parameters used in the modeling of these ten FIR filters and their applications include the following;

1. Sampling frequency; 1000Hz
2. Filter type; band stop filters
3. Upper band cut-off frequency; 60Hz
4. Lower band cut-off frequency; 40Hz
5. Noise type; 50Hz 5mV PLI
6. Filter order; 100, 120 and 140
7. Simulation application; MATLAB
8. Analysis tool; MSE

III. ANALYSIS TOOL

Analysis on the performance of the each of the ten windows is based on MSE. This analytical tool is applied on each of the filters. Results emanating from various filters as obtained from simulated program in MATLAB application are analyzed and compared with each other. MSE of two functions measures the average of the squares of the errors of functions that is, the average squared difference between the estimated values and the actual value. It can further be defined as the mean $\frac{1}{n}\sum_{i=1}^{n}$ of the difference of square of functions y and x $(y_i - x_i)^2$. Thus MSE is expressed as shown in equ 11.

$$MSE=\frac{1}{n}\sum_{i=1}^{n}(y_i-x_i)^2 \qquad \text{Equ 11}$$

In the application of MSE, the value that has the least entry makes the least MSE. That means that the window least MSE makes the best result in this evaluation.

IV. RESULTS OBTAINED

After the application of the ten FIR filters on EEG signal corrupted with 50Hz. Analysis on of each of the ten filters was conducted using each of the filters. Equ 11 for MSE was simulated with MATLAB and applied in the process. Vectors representing EEG signals (y_i) and filtered EEG signals (x_i) for each of the filters were applied. Evaluations on the values of MSE for each of the filters were made using filter orders 100, 120 and 140. The results obtained in the process are summarized as tabulated in Table 1. Summary of the data displayed in table 1 show that for filter order 100, the HAS Window makes the best MSE among all other windows followed by the Hamming Window. MSE for the HAS Window is equal to 136.5043 and MSE for the Hamming Window is equal to 136. 5637.

For filter order 120, the Rectangular Window followed by Kaiser Window made the best MSE. From the tabulated data in table 1, it can be shown that the Rectangular Window has MSE value of 139.8768 while Kaiser Window has value of 140.1684. Lastly for filter order 120, Welch Window has the best MSE of 158.5979 followed by Hann Window’s value mark of 158.6399.

V. CONCLUSION

FIR filters modeled with HAS Window, Rectangular Window and Welch Window, made the best MSE values for filter orders 100, 120 and 140 respectively. With the same filter orders, Hamming Window, Kaiser Window and Hann Window in that order made the second best MSE. While, the worst MSE seen among the ten windows are from those of Blackman Harris Window for filter order 100, Hann Window for filter order 120 and Kaiser Window for filter order 140. This shows that varying the filter order of an FIR filter influences the performance of FIR filter. From the result analysis made above, the following can further be deduced;

1. The value of filter order affects the MSE value of windows.
2. FIR filter performance is dependent on the filter order used.

Table 1; SNR for different windows on filter orders 100, 120 and 140

Window	**MSE**		
	L = 100	**L = 120**	**L = 140**
Kaiser	136.8580	140.1684	166.5289
Parzen	140.0354	141.9267	160.1688
Gaussian	137.4061	142.3452	159.2477
Hann	136.7636	143.0163	158.6399
Hamming	136.5637	142.5804	159.3216
Rectangular	137.0420	139.8768	167.1478
Nuttall	140.3583	141.6971	160.3469
Blackman Harris	140.5028	141.6791	160.4249
HAS	136.5043	141.4020	159.2486
Welch	136.0566	142.4779	158.5979

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