Performance Analysis of Various Infinite Impulse Response (IIR) Digital Filters in the Reduction of Powerline Interference in ECG Signals

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Abstract-Electrocardiography (ECG) system measures heart activity over time by measuring electric potentials on the surface of living tissue. An ECG system can detect problems the heart has with heart rhythm, fundamental frequency, pressure and strength. It assists medical doctors in ascertaining someone that is having heart attack or has had heart attack in the past. The system can indicate if a heart is enlarged or thickened. Electrocardiography generates a signal known as ECG signal and it is this signal that is measure by an ECG system. The characteristic of the signal is a measure of the health condition of the heart. Naturally this signal is combined with various kinds of signals which constitute noises to it and the main ones are powerline interference, baseline wander, electromyogram and electroencephalogram. With this combination, the integrity of the ECG signal cannot be determined, and clinical interpretations may be erroneous. It is necessary to remove these noises and different types of digital filters can be employed. In this paper only the removal of powerline interference is considered, and a comparative analysis of the effectiveness of four different types of infinite impulse response filters in the removal is presented. Matlab software is used to generate the signals and observe

and record results

Keywords: ECG, Filters, Magnitude Response, Signal to Noise Ratio

1. Introduction

The field of biomedical signal processing and analysis has advanced to the stage of practical application of signal processing and analysis techniques for efficient and improved diagnosis and monitoring of critical patients. Electrocardiographic (ECG) signal is an important clinical signal for investigating the activities of heart. Interpretation of the details provides for diagnosis of a wide range of heart conditions. Incidentally this ECG signal is mixed with other biomedical signals and the powerline noise signal from the power source supplying the recording equipment or electrocardiograph, also abbreviated ECG. These signals mixing with the ECG effectively contaminate it and degrade its quality. For correct interpretation of the features of the ECG signal, these contaminating signals must be removed from the ECG.

Digital filters are used to remove these contaminating signals. There are different types of digital filters that can be used to effect the removal. In [1] Jurko and Rozinaj used polynomial approximation to remove interference in ECG. The authors stated that polynomial in this sense is a finite impulse response (FIR) filter with moving window according to the order of the polynomial. Chandrakar and Kowar [2] applied recursive least square algorithm to remove powerline interference components of fundamental frequency and the harmonics from ECG signal among other interferences. Geeta and Bhaskar [3] carried out a design and development of FIR equiripple filter for reducing powerline interference in ECG signal and compared its performance with least square and window methods. In [4] Sonal and Uplane designed and developed digital chebyshev Type II low pass, high pass and notch filters for removing the Electroencephalogram, baseline wander and powerline noise contaminating ECG signals respectively. In [5] Mahesh et al did a comparative study of the effectiveness of Chebyshev I and Chebyshev II digital filters in removing noises in

ECG. The authors also examined the difference in performance between the two Chebyshev filters, Butterworth and elliptic filters. In [6] Manpreet and Birmohan exploited the effectiveness of the combination of moving average method and IIR notch to filter powerline interference and baseline wander in ECG. Mahesh et al [7] designed and developed elliptic digital filters and applied them to removal of different noises that corrupt ECG signal. Yatindra and Gorav [8] did a performance analysis of three different types of digital filters to reduce powerline interference in ECG. The filters are notch filter for frequency domain filtering, Wiener filter for optimal filtering and adaptive filter for adaptive filtering. Mahesh et al in [9] applied Chebyshev type II digital filter to reduce various noises that degrade ECG signals. In [10] Manish et al designed and implemented Butterworth, Chebyshev type I, chebyshev type II and eleiptic digital filters and compared their performances in removing power supply noise in ECG. Mikhed and Khaled [11] approached denoising of ECG signal by Wavelet transform thresholding. This is not a digital filter but an algorithm which is effective in removing low frequency noise in ECG. Mahesh et al in their work [12] demonstrated how chebyshev I digital ECG can be used to remove interference in ECG. In [13] Thenua and Agarwal presented an implementation of least mean square (LMS),normalized least mean square (NLMS) and recursive least square (RLS) algorithms in matlab environment and compared their performance in noise cancellation. This implementation can be adapted topowerline interference reduction in ECG. In [14] Mahesh et al designed and implemented digital FIR equiripple notch filter and used it to remove powerline interference in ECG. The filter performed satisfactorily. Hon Wan et al [15] used LMS based adaptive filter to filter off the 50Hz powerline interference in ECG. Daniel et al [16] demonstrated how variation of step-size parameter in an adaptive notch filter based on LMS algorithm removes powerline interference in ECG. The authors compared the performance with that of fixed step-size parameter adaptive filter and the result shows that the variable step-size parameter scheme out-performed the fixed step-size parameter scheme. Dhillon and Chakrabarti [17] used lattice-based second order infinite impulse response (IIR) notch filter with a simplified adaptation algorithm for removal of powerline frequency from ECG signals. The filter exhibited superior performance over second order static coefficient IIR filter in removing the interference in ECG.

In this paper we propose to examine the performance of four different types of IIR digital filters in removing powerline interference in ECG. The four filters are Butterworth, Chebyshev type I, Chebyshev type II and elliptic notch filters.

1. Signal to Noise Ratio (SNR) of Filtered ECG Signals

Signal to noise ratio (SNR) of the filtered ECG signal is the evaluation measure that will be used to determine the filtration strength of each of the four filters being dealt with in this paper. Signal to noise ratio is measure of the proportion of noise present in a signal. The expression for the computation is given in eqn (1)

$$SNR = 10Log\frac{\sum S^2}{\sum N^2} \qquad (1)$$

where N is the noise power present in the signal, while S is the power of the signal.

For a filtered signal the signal to noise ratio is given sa in eqn (2)

$$SNR_o = 10Log\frac{\sum S_F^2}{\sum N_o^2} \qquad (2)$$

where No, the output noise power, is the noise power present in the filtered signal while S_F is the power of the filtered signal. Output noise power No is given by

$$No = S - S_F \qquad (3)$$

where S is the power of the unfiltered signal. Using (3) in (2) gives (4)

$$SNR_o = 10Log\frac{\sum S_F^2}{\sum (S - S_F)^2} \qquad (4)$$

For one level noise the output signal to noise ratio from (4) is

$$10\log\frac{S_F^2}{(S - S_F)^2} \qquad (5)$$

Renumadhavi et al [18] developed a new approach for finding the the SNR of filters with respect to filtering powerline interference in ECG. The new method uses

Noise Power=Mean Square Difference Between Actual and Expected Signal

2. Design of Digital IIR Notch Filters

The general digital transfer function of IIR filter is

$$H(z)=\frac{b_0+b_1Z^{-1}+b_2Z^{-2}+b_3Z^{-3}+.......+b_NZ^{-N}}{1+a_1Z^{-1}+a_2Z^{-2}+a_3Z^{-3}+.......+a_NZ^{-N}} \quad (6)$$

where $b_{0,}$ b_1, b_2……..b_N and $a_{1,}$ $a_{2,}$ ....a_N are filter coefficents. The order of the filter is N either in the numerator or denominator polynomials, which ever one is higher. The values of the filter coefficients differentiate one IIR filter from the other both in terms of frequency response (high pass, low pass, band pass or band stop) and ripple nature (Butterworth, Chebyshev I, Chebyshev II or Elliptic). Designing IIR filter involves first, parameter-specification, which includes frequency and ripple specification. With this specification the order of the filter is determined. With the filter order, the filter coefficients are computed. Substituting the filter coefficients in (6) forms the specific transfer function of the filter being designed. The transfer function of the filter in frequency domain is obtained by substituting $Z=e^{jw}$ in (6). Using the specifications on a matlab function for each IIR filter quickly and accurately generates the order of the filter and the filter coefficients for such a filter.

3.1 Design of Butterworth Notch Filter

With a powerline interference frequency of 50Hz and sampling frequency of 1000Hz, the order of the filter by matlab command is 4 and the filter coefficients are b= 0.9489, -3.6103, 5.3319, -3.6103 and 0.9489, and a= 1.0000, -3.6845, 5.2707, -3.4604 and 0.8825. Putting the filter coefficients in eqn (6) provides the transfer function of the filter as in eqn (7). The impulse and magnitude responses are depicted in fig. 1 and fig. 2

$$H(z) = \frac{0.9489-3.6103z^{-1}+5.3319z^{-2}-3.6103z^{-3}+0.9489z^{-4}}{1.0000-3.7051z^{-1}+5.3293z^{-2}-5.5156^{-3}+0.9004z^{-4}} \quad (7)$$

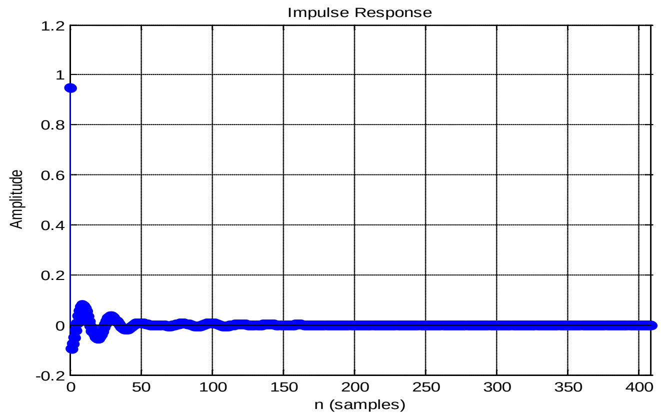

Fig. 1: Impulse Response of Butterworth Notch Filter

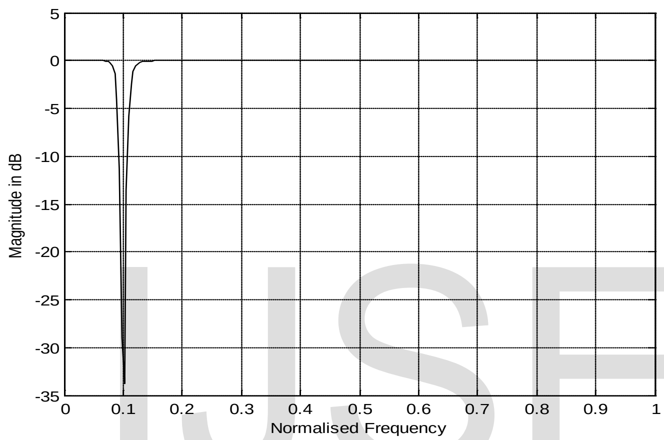

Fig. 2: Magnitude Response of Butterworth Notch Filter

3.2 Design of Chebyshev I Notch Filter

Using a sampling frequency of 1000Hz on the powerline interference of 50Hz produces the order of the filter as 4 and the filter coefficients as b= 0.7886, -3.0058, 4.4415, -3.0058 and 0.7886, and a= 1.0000, -3.6845, 5.2707, -3.4604 and 0.8825. The transfer function of the filter is as in eqn (8) and the impulse and magnitude responses are depicted in fig 3and fig. 4.

$$H(z)=\frac{0.7886-3.0058z^{-1}+4.4415z^{-2}-3.0058z^{-3}+0.7786z^{-4}}{1.0000-3.68451z^{-1}+5.2707z^{-2}-3.4604z^{-3}+0.8825z^{-4}} \quad (8)$$

$$H(z) = \frac{0.9668-3.6779z^{-1}+5.4314z^{-2}-3.6779z^{-3}-0.9668z^{-4}}{1.0000-3.7400z^{-1}+5.4303z^{-2}-3.6158z^{-3}+0.9347z^{-4}} \quad (9)$$

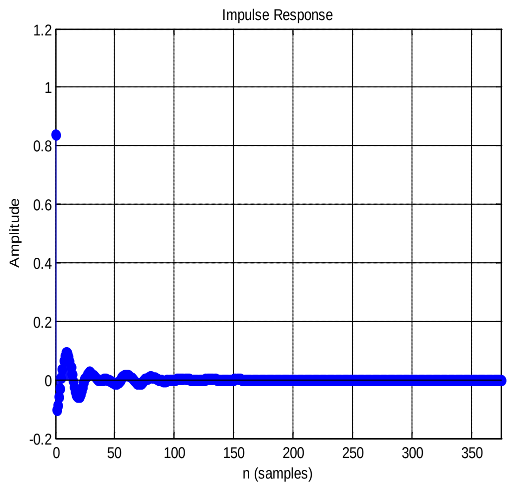

Fig. 3: Impulse Response of the Chebyshev I Notch Filter

3.3 Design of Chebyshev II Notch Filter

The sampling frequency for the design is 1000Hz and the powerline interference frequency is 50Hz. Based on these specifications the order of the filter is 4 and

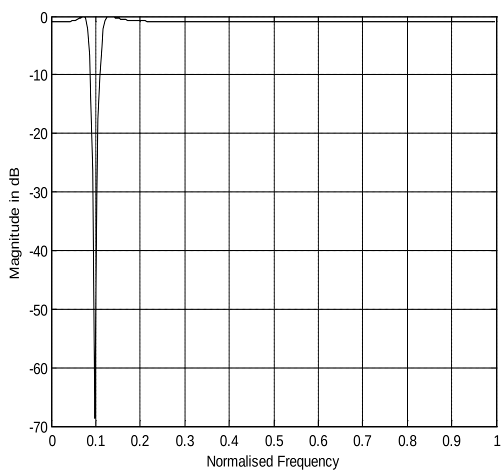

Fig. 4: Magnitude Response of the Chebyshev I Notch Filter

the filter coefficients are b= 0.9668, -3.6779, 5.4314, -3.779 and 0.9668, and

a= 1.0000, -3.7400, 5.4303, -3.6158 and 0.9347. The transfer function of the filter based on the filter coefficients is as in eqn (9) above. The impulse and magnitude responses are shown in fig. 5 and fig. 6.

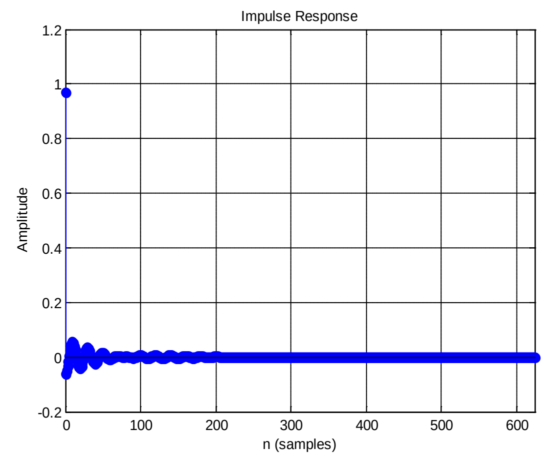

Fig. 5: Impulse Response of the Chebyshev II Notch Filter

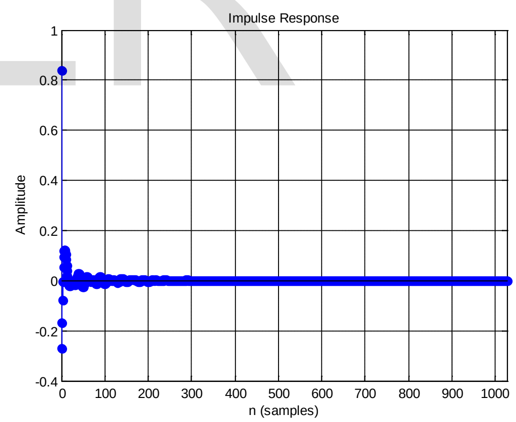

Fig.7: Impulse Response of the Elliptic Notch Filter

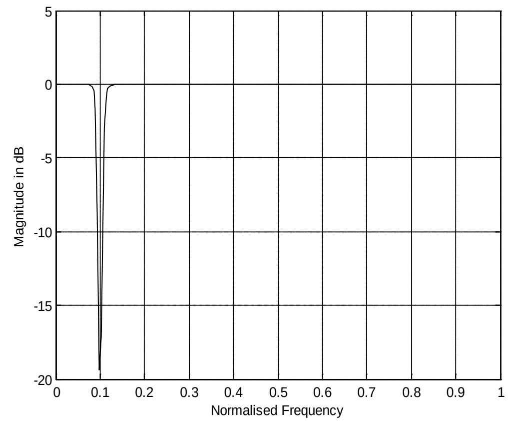

Fig. 6: Magnitude Response of Chebyshev II Notch Filter

3.4 Design of Elliptic Notch Filter

The sampling frequency for the design is 1000Hz while the powerline interference frequency is 50Hz. Based on these specifications the order of the filter is 6 and the filter coefficients are b= 0.8366, -4.7818, 11.6203, -15.3494, 11.6203, 4.7818 and 0.833, and a= 1.0000, -5.3899, 12.3356, -15.3243, 10.8917, -4.1988 and 0.6863. The transfer function of the filter based on the filter coefficients is as in eqn (10). The impulse and magnitude responses are shown in fig. 7 and fig. 8.

$$\boldsymbol{H(z)} = \frac{\mathbf{0.8366 - 4.7818z^{-1} + 11.6203z^{-2} - 15.3494z^{-3} + 11.6203z^{-4} - 4.7818z^{-5} + 0.8366z^{-6}}}{\mathbf{1.0000 - 5.3899z^{-1} + 12.3356z^{-2} - 15.3243z^{-3} + 10.8917z^{-4} - 4.1988z^{-5} + 0.6863z^{-6}}}$$

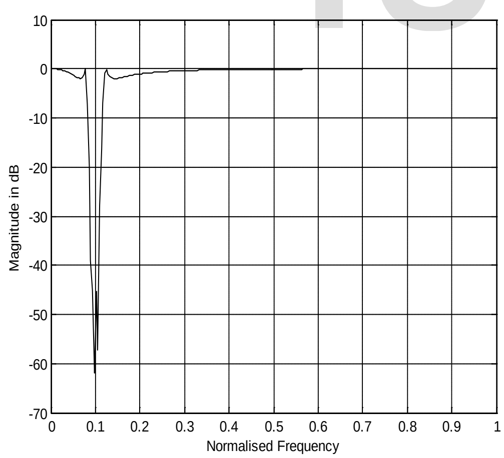

Fig. 8 Magnitude Response of the Elliptic Notch Filter

4. Results

Fig. 9 shows an uncorrupt ECG signal containing 4 cycles from a heart beat of about 89 bps. The ECG signal is made corrupt with a 50Hz powerline interference and the corrupt signal is shown in fig 10. The corrupt ECG signal is filtered separately with the four different notch filters in sequence and the filtered signals are presented in figures 11, 12, 13 and 14. The signal to noise ratios of the filtered ECG signals at 50Hz are computed by means of eqn (5) and the values are presented as in table 1. The power of the unfiltered ECG signal at 50Hz is **15.03dB**.

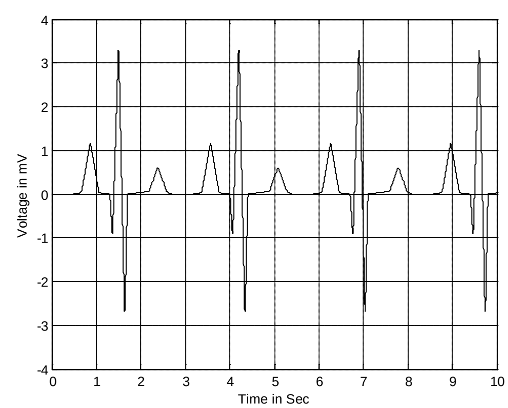

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Fig. 9: ECG Signal Showing Four Cycles

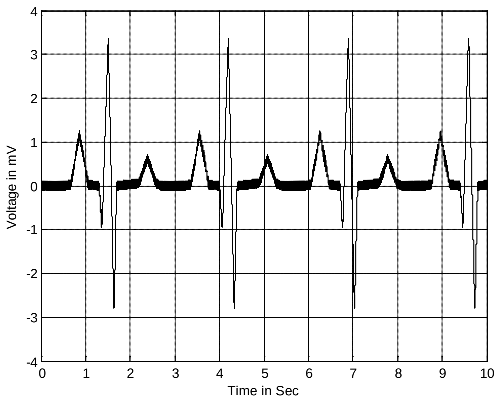

Fig. 10: ECG signal Corrupt with 50Hz Powerline Noise

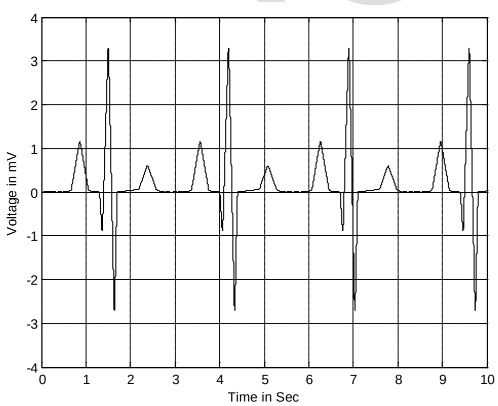

Fig. 11: ECG signal Filtered with Butterworth Notch Filter

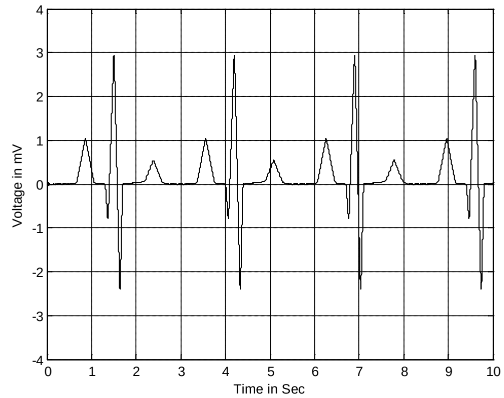

Fig. 12: ECG signal Filtered with Chebyshev I Notch Filter

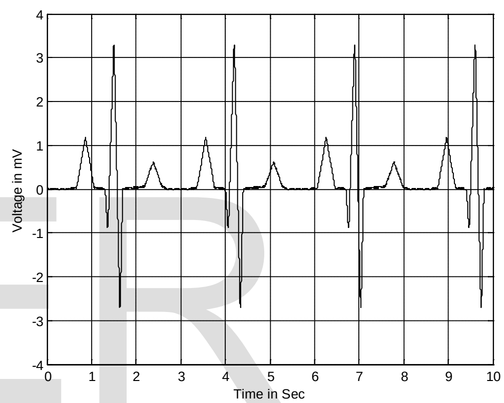

Fig. 13: ECG signal Filtered with Chebyshev II Notch Filter

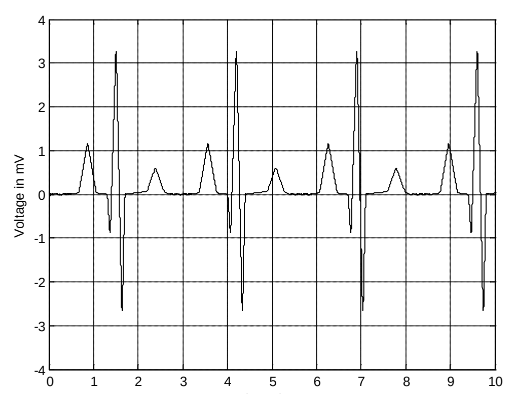

Fig. 14: ECG signal Filtered with Elliptic Notch Filter

Table 1: Signal to Noise Ratios of ECG Signals at 50Hz Filtered with Notch Filters Designed with Different Windows

Type of Filter	Order of Filter	Signal to Noise Ratio (SNR) of Filtered ECG in dB
Butterworth	4	150.30
Chebyshev I	4	81.60
Chebyshev II	4	29.75
Elliptic	6	97.39

5. Discussion

The impulse responses of the four filters as depicted in figures 1, 3, 5, and 7 show that the filters are stable because the amplitude quickly collapsed to zero as time progresses from zero. Stability of the filters is also confirmed from the magnitude responses of figures 2, 4, 6 and 8 as no sustained oscillation is observed in each of the responses. Close observations of the unfiltered signal of fig. 10 and filtered signals of figures 11 to 14 and comparing them with the corrupt-free signal of fig. 9 suggests that each of the four filters substantially removed the 50Hz powerline noise in the ECG. The signal to noise ratios in/ table 1 informs that Butterworth filters is comparatively the most effective in reducing powerline interference in ECG followed by the elliptic filter, while Chebyshev II filter is the least effective. It is therefore recommended that in consideration of the four filters Butterworth filter should be used in designing notch filters for the removal of powerline interferences in ECG. Its ripple free characteristic in both pass and stop bands is also desirable.

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