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# A Pole Radius Varying Notch Filter with Transient Suppression for Electrocardiogram

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***Abstract*—**Noise removal techniques play a vital role in the performance of electrocardiographic (ECG) signal processing systems. ECG signals can be corrupted by various kinds of noise such as baseline wander noise, electromyographic interference, and powerline interference. One of the significant challenges in ECG signal processing is the degradation caused by additive 50 or 60 Hz powerline interference. This work investigates the removal of power line interference and suppression of transient response for filtering noise corrupted ECG signals. We demonstrate the effectiveness of infinite impulse response (IIR) notch filter with time varying pole radius for improving the transient behavior. The temporary change in the pole radius of the filter diminishes the transient behavior. Simulation results show that the proposed IIR filter with time varying pole radius outperforms traditional IIR notch filters in terms of mean square error and transient suppression.

***Keywords*—**Notch filter, ECG, transient, pole radius.

## I. Introduction

ELECTROCARDIOGRAM (ECG) signals show the electrical activity of the heart for analyzing the health of a patient. Computer aided analysis of ECG signals is a rapidly growing research area. The noise present in ECG signals poses a significant challenge in accurate analysis and interpretation of data. ECG signals are usually corrupted by various noises such as baseline wander noise, powerline interference, and motion artifacts. To reduce the effect of noise, filters are widely used for processing ECG signals. Recently several researchers have addressed effective noise removal in ECG signals [1]-[6]. The most common form of noise in ECG signals is caused by power line interference. Power line interference is easily recognizable since the interfering voltage in the ECG signal may have a spike in the frequency range 50-60 Hz. For real time ECG signals, the power line frequency varies over a narrow range of frequencies centered around 50Hz. For the reduction of the powerline interference, typically a fixed or adaptive notch filter is used [7]-[9]. Recently, researchers have also investigated the ability of nonlinear filters for ECG signal processing [2], [10]. Recent work has also investigated the use of FIR and IIR filters for noise removal in ECG signals [11].

Their work concluded that IIR filters outperform FIR filters with regards to the number of filter coefficients and complexity. Although the approaches proposed in [7]-[11] are interesting; they do not examine the problem of the reduction of transient duration in IIR notch filters. Recent research has shown that notch filters with time varying pole radius can improve the transient response of the filter output [12], [13]. However, there has been very limited work in exploring the application of pole varying notch filter for ECG transient suppression. In this work, we demonstrate the effectiveness of higher order notch filters with time varying pole radius for efficient suppression of transient response in ECG signals. Our work examines the effect of both the filter order and the time varying pole characteristic for removal of powerline interference. We perform extensive simulations based on data from the MIT-BIH arrhythmia data base [14]. Our results show that the proposed notch filter with time varying pole radius significantly outperforms traditional notch filtering techniques. The rest of the paper is organized as follows. Section II presents the principles and techniques of IIR notch filters. In Section III, we describe the IIR notch filter with time varying pole radius. Section IV presents our simulation results and performance comparison of different notch filters. Concluding remarks are presented in Section V.

## II. IIR Filter Design

A recursive filter has feedback from output to input. Hence, the output is a function of previous output samples and the present and past input samples. This can be described by the following equation. Consider a digital filter with input x[m] and output y[m]. The relationship between the input and output signal for a digital filter of order N is defined as

$$y[m]=\sum_{k=1}^{N}(a_k y[m-k])+\sum_{k=0}^{N}(b_k x[m-k]) \tag{1}$$

where $a_k$ and $b_k$ are the filter coefficients. When a recursive filter is excited by an impulse function, the output lasts forever. Such filters are called infinite duration impulse response (IIR) filters. The transfer function of anIIR filter can be expressed using Z transform as

$$H(z)=\frac{\sum_{k=0}^{N} b_k Z^{-k}}{1+\sum_{k=1}^{N} a_k Z^{-k}} \tag{2}$$

For a second order filter, the transfer function is given as

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$$H(z)=\frac{1+b_1z^{-1}+b_2z^{-2}}{1+a_1z^{-1}+a_2z^{-2}} \tag{3}$$

Fig. 1 shows the structure of a second order IIR filter. The structure shown in the figure can be cascaded to obtain higher order filters as shown in Fig. 2.

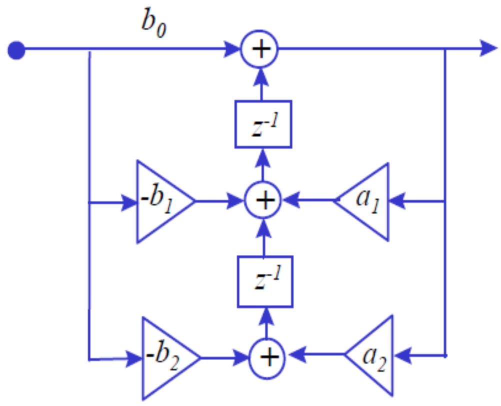


Fig. 1 Realization of a second order IIR filter

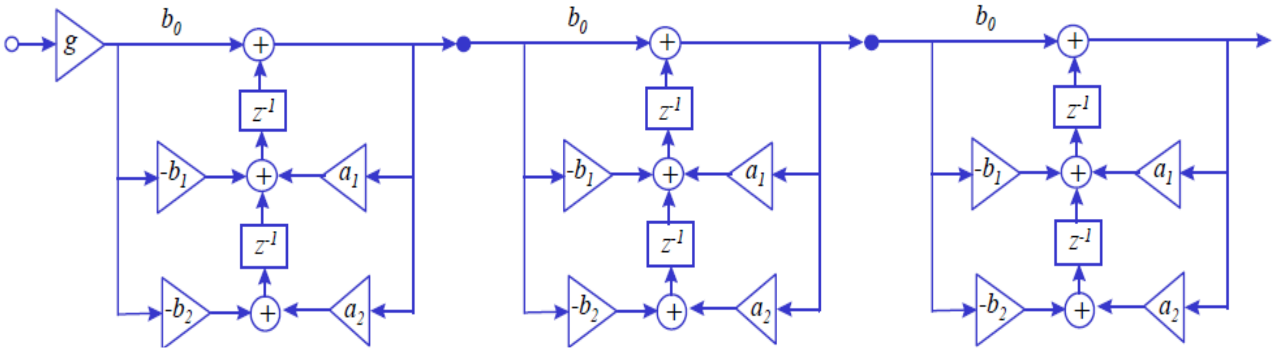


Fig. 2 Realization of a cascade IIR structure from second order filters

We used a pole-zero placement method for designing the IIR notch filter. The radius of the pole is given by

$$r=1-\frac{\Delta f}{f_s} \tag{4}$$

where $fs$ is the sampling frequency and $\Delta f$ is the ideal bandwidth of the rejected band. The pole location $\Theta_0$ is determined using

$$\theta_0=\frac{2\pi f_0}{f_s} \tag{5}$$

Based on the pole location and radius, the transfer function of a second order IIR notch filter is given as

$$H(z)=\frac{1-2\cos(\theta_0)z^{-1}+z^{-2}}{1-2r\cos(\theta_0)z^{-1}+r^2z^{-2}} \tag{6}$$

A higher value of pole radius results in narrower bandwidth with greater filter selectivity. As the pole radius increases, the transient response of the filter is also increased. Fig. 3 shows the variation in transient response for different pole radius for a first order notch filter. This concept is described in detail in [12].

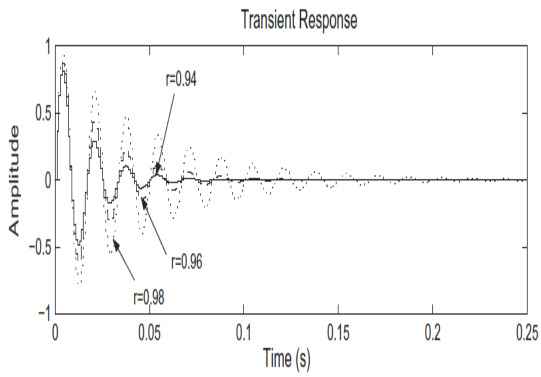


Fig. 3 Transient response of a first order notch filter

To reduce the duration of the transient behavior, the pole radius can be changed with time. In the next section, we describe the principles of IIR filer with time varying pole radius

## III. IIR Filter with Time Varying Pole Radius

The transient response of an IIR filter can be improved by varying the pole radius with time. The relation between the input and output of such a filter can be described as

$$y[m] = \sum_{k=0}^{N} b_k x[m-k] - \sum_{k=1}^{N} r^k(m) a_k y[m-k] \quad (7)$$

The function *r(m)* defines the time varying radius of the poles. The transient behavior of the filter diminishes with a decrease in the pole radius. Hence, to improve the response of the notch filter, the pole radius should be reduced when the filter displays transient behavior at the output. The pole radius can be varied with time using the following equation proposed in [12]

$$r(m) = \bar{r} \times \left\{1 + (\beta - 1)\exp\left(\frac{-n}{\alpha f_s}\right)\right\} \quad (8)$$

where α is the damping rate of the pole radius and the coefficients β and $\bar{r}$ are defined as

$$\beta = \frac{r(0)}{\bar{r}} \text{ and } \bar{r} = \lim_{n\to\infty} r(n) \quad (9)$$

The exponential function enables the pole radius to grow from an initial value r(0) to the desired value $\bar{r}$. The parameter α is provided as a design specification and β can be determined based on computer simulations as described in [12].

The performance of the notch filter can be determined using mean square error which is defined as

$$MSE = \frac{1}{N}\sum_{n=1}^{N}(y[n] - x[n])^2 \quad (10)$$

where N is the number of samples, x[n] is the input to the filter, and y[n] is the output of the filter.

## IV. Simulations

The main objective of our simulations is to compare the performance of traditional IIR notch filter with the proposed time varying pole radius based notch filter. Our simulations were performed in Matlab using the MIT ECG data base [14]. The sample frequency $f_s$ and filter pole radius $\bar{r}$ were set to 1.5 KHz and 0.98 respectively. For the time varying pole radius in (8), the parameters were set as follows: β= 0.9 and α=2.8. To compute the MSE, we set the number of samples N=1000. Fig. 4 shows the spectrum of the ECG signal. The spike at a frequency of 60 Hz seen in Fig. 4 corresponds to powerline interference.

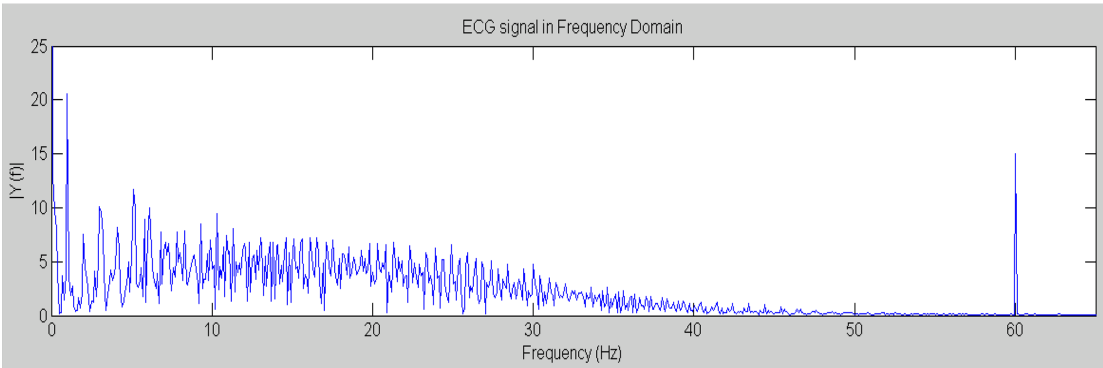


Fig. 4 Spectrum of ECG signal

Figs. 5 and 6 show the performance comparison of the traditional notch filter with the time varying pole radius based notch filter for filter orders two and six respectively. It is evident from the figures that the performance improves with increase in filter order. We also observe that the time varying pole radius based notch filter outperforms traditional notch filters by achieving significantly better transient suppression.

Fig. 7 shows the mean squared error (MSE) vs. increasing filter orders for traditional and pole radius varying notch filters. The results show that as the filter order increases the MSE decreases. We observe that the notch filter with time varying pole radius outperforms the traditional notch filter for various filter orders.

Fig. 7 also shows that the notch filter with time varying radius achieves an MSE of 0.01 for an 8th order filter while the traditional notch filter obtains an MSE of 0.2. A smaller MSE implies a shorter transient duration. Hence, it is clear that the proposed time varying pole radius notch filter is effective in reducing transient response compared to traditional filters. It is also worth noting that higher order filters achieve lower MSE at the cost of increase in processing power and complexity.

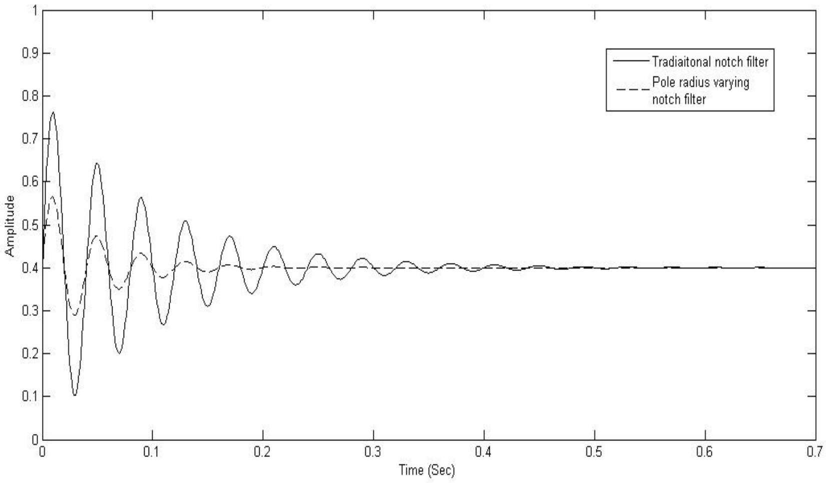


Fig. 5 Comparison of traditional and pole radius varying notch filters where the filter order N=2

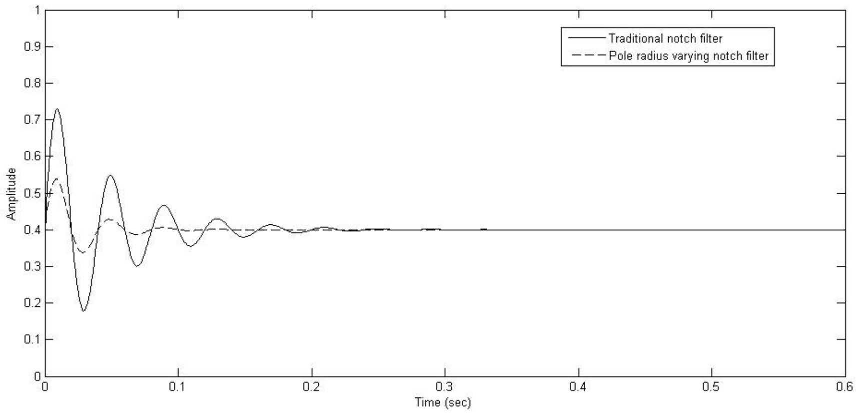


Fig. 6 Comparison of traditional and pole radius varying notch filters where the filter order N=6

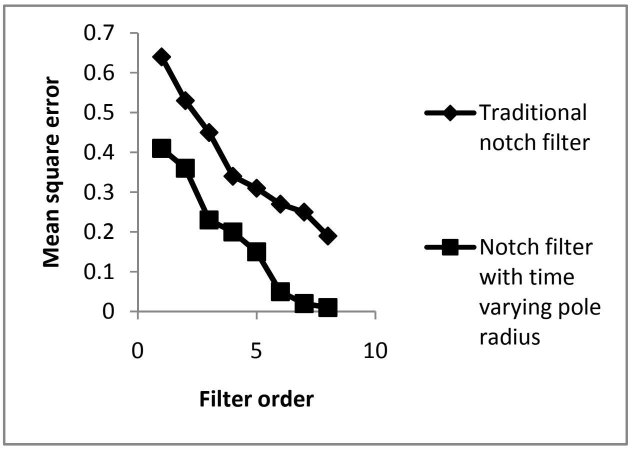


Fig. 7 Variation of mean square error with filter order

## V. Conclusions

ECG signals can be corrupted by various kinds of noise such as baseline wander noise, electromyographic interference, and powerline interference. Removal of noise plays a significant role in the analysis of ECG signals. In this work, we demonstrated the capability of time varying pole radius notch filters for removal of powerline interference and transient suppression. Extensive simulations were performed to compare the performance of the proposed filter with traditional time invariant filters. Our results showed that notch filters with time varying pole radius were successful in removing the noise and suppressing the transient response. The mean square error was considerably reduced by the proposed notch filters compared to traditional notch filters. Our future work will investigate analytical closed form solutions for the parameters of the time varying pole radius. We are also interested in investigating the utility of the time varying pole radius filters for noise removal in other biological signals such as electro encephalogram signals.

## References

[1] V. Almenar and A. Albiol, A New Adaptive Scheme for ECG Enhancement. Signal Processing, 75(3), 1999, pp. 253 –263.
[2] J. M. Leski, and N. Henzel, ECG Baseline Wander and Powerline Interference Reduction Using Nonlinear Filter Bank. Signal Processing, 85(4), 2005, pp.781 – 793.
[3] M. Kotas, Projective Filtering of Time-Aligned ECG Beats for Repolarization Duration Measurement. Computer Methods and

Programs in Biomedicine, 85(2), 2007, pp.115 – 123.
[4] M. Korrek and A. Nizam, Clustering Mit-Bih Arrhythmias with Ant Colony Optimization Using Time Domain and PCA Compressed Wavelet Coefficients. Digital Signal Processing, 20(4), 2010, pp.1050 – 1060.
[5] D. Bansal, M. Khan, and A. K. Salhan, A Computer Based Wireless System for Online Acquisition, Monitoring and Digital Processing of ECG Waveforms. Computers in Biology and Medicine, 39(4), 2009, pp. 361 – 367.
[6] J. Yan, Y. Lu, J. Liu, X. Wu, and Y. Xu, Selfadaptive Model-Based ECG Denoising Using Features Extracted by Mean Shift Algorithm. Biomedical Signal Processing and Control, 5(2), 2010, pp.103 – 113.
[7] M. Ferdjallah, R.E. Barr, Adaptive Digital Notch Filter Design on the Unit Circle for the Removal of Powerline Noise from Biomedical Signals, IEEE Trans. Biomed. Eng. 41 (4), 1994, pp. 529–536.
[8] S.-C. Pei, C.-C. Tseng, Elimination of AC Interference in Electrocardiogram Using IIR Notch Filter with Transient Suppression, IEEE Trans. Biomed. Eng. 42 (7), 1995, pp. 1128–1132.
[9] N.V. Thakor, Y.-S. Zhu, Application of Adaptive Filtering to ECG Analysis: Noise Cancellation and Arrhythmia Detection, IEEE Trans. Biomed. Eng. 38 (8), 1991, pp.785–794.
[10] C.-H.H. Chu, E.J. Delp, Impulsive noise Suppression and Background Normalization of Electrocardiogram Signals Using Morphological Operators, IEEE Trans. Biomed. Eng. 36 (2), 1989, pp. 262–273.
[11] A.S Khaing and Z. M. Naing, Quantitative Investigation of Digital Filters in Electrocardiogram with Simulated Noises, International Journal of Information and Electronics Engineering, 1 (3), 2011.
[12] J. Piskorowski, Digital Q-Varying Notch IIR Filter with Transient Suppression, IEEE Trans. Instrum. Meas. 59 (4), 2010, pp. 866–872.
[13] L. Tan, Pole-Radius-Varying IIR Notch Filter With Transient Suppression‖, in IEEE Transactions on Instrumentation and Measurement, Vol. 61, 2012, pp. 1684 - 1691.
[14] A.L. Goldberger, L.A.N. Amaral, L. Glass, J.M. Hausdorff, P.C. Ivanov, R.G. Mark, J.E. Mietus, G.B. Moody, C.-K. Peng, H.E. Stanley, PhysioBank, PhysioToolkit, and PhysioNet: Components of a New Research Resource for Complex Physiologic Signals, Circulation 101.