Improvement of SNR by Removing Power-line Interference from Noisy ECG Signal

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The electrical signals are invariably accompanied by components that are unrelated to the phenomenon being studied. Spurious or unwanted signal components which may occur at any frequency within band pass of the system are known as noise. The instruments are designed in such a way that the noise is minimized to facilitate accurate and sensitive measurement. Noise in Electrocardiograph (ECG) recording occurs due to high frequency Electromagnetic (EM) noise, motion artifacts and power line (50Hz or 60Hz) interference. For extraction of information from noisy signals, it is essential to increase or improve Signal to Noise ratio (SNR) which ultimately improves the performance. To process the signal waveform without distortion, the band pass of the system must be introduced such that all the frequency components of the signal contribute to signal strength. Most signal conditioners include low-pass filters designed specifically to provide maximum rejection of 50Hz noise. Such filters are called "notch filters". Notch filters having only zeros in transfer function has very wide notch bandwidth and offers more attenuation at adjacent frequencies. In this paper we use Notch filter with poles added at multiple point of a unit circle (0<Radius(r) <1) improves the performance by narrowing the notch bandwidth and decreasing attenuation at adjacent frequencies. Comparing five cases of different pole zero location with reference to radius 0.99, we got best performance in case-5 where the Signal to Noise ratio is observed to be 32.36 dB. As the signal to noise ratio increase, the stability of the system increases and system response also improved. As the poles move closer to zeros, notch bandwidth decreases and approaches ideal notch filter.

Keywords: Filtering, Noise, Pole and Zero, EM, ECG

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1 Introduction

Information obtained from the electrodes/transducers is often in terms of current intensity, voltage level, frequency or signal phase relative to a standard. In addition to handling the specific outputs from these devices, signal conditioners are used in biomedical instruments to perform a variety of general-purpose conditioning functions to improve the quality, flexibility and reliability of the measurement system. Important functions performed by signal conditioners are signal amplification, frequency response, filtering, isolation, excitation [1]. Electrocardiograph (ECG) is an instrument which records the electrical activity of the heart. ECG provides valuable information about a wide range of cardiac disorders such as presence of an inactive part or an enlargement of the heart muscle.

2 Power line Interference

Abnormal patterns of ECG may be due to pathological states or an occasion that may be due to artifacts [2]. These are: (a) interference from the power line (b) shifting of the base line (c) Muscle Tremor. Power line interference is easily known since the interfering voltage in the ECG would have a frequency of 50Hz or 60Hz [3]. This interference may be due to the stray effect of the alternating current on the patient or because of alternating current fields due to loops in the patient cable. Other causes of interference are loose contacts on the patient cable as well as dirty electrodes [4]. When the machine or the patient is not properly grounded, power line interference may even completely affect the ECG waveform. The input ECG signal which is sampled at 200Hz with a significant amount of 60Hz power line artifact is shown in Fig-1.

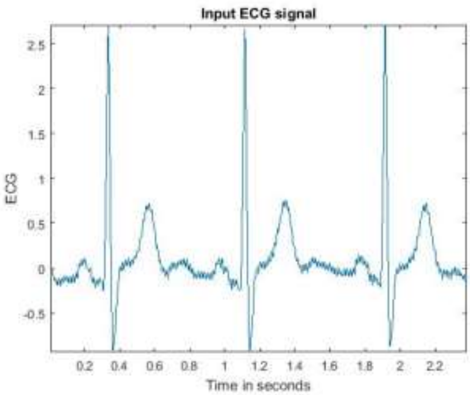


Figure 1: Input ECG with power line artifact at 60Hz

The most common cause of 50Hz interference is the disconnected electrode resulting in a very strong disturbing signal. Sometimes static charges may result in a random noise on the trace [5]. A practical solution to minimize this problem is to have a physical separation between the interference causing sources and the patient.

3 Digital Notch Filtering

A filter is a circuit which passes some of the frequencies applied to its input and attenuates others [6]. There are four common types of filtering: high pass, low pass, band pass, band stop. High pass which only passes frequencies above a certain value; low pass, which only passes frequencies below a certain value; band pass which passes frequencies within a certain band; and band stop, which passes except those in a certain band. Filters are also classified based on the nature of the input and the output signals into two types. These are analog filters and digital filters.

3.1 Notch Filter

Additionally signal conditioners also include filters to reject unwanted noise within certain frequency range. Almost all measuring and recording applications are subject to some degree of 50Hz noise picked up from power lines or machinery [7]. Therefore, most signal conditioners include low-pass filters designed specifically to provide maximum rejection of 50Hz noise. Such filters are called “notch fitters”.

3.2 Digital Notch Filter

These filters processes and generates digital data that have several advantages over analog filters. They are relatively insensitive to temperature, ageing, voltage drift and external interference as compared to analog filters. Their response is completely reproducible and predictable, and software simulation can exactly reflect better product performance [8].

A digital notch filter with f_o =60 Hz and only zeros i.e., a FIR filter having transfer function in z-domain is represented in Equation. (1) as given below [9]

$$H(z) = \frac{B(z)}{A(z)} = \frac{b0 + b1z^{-1} + \cdots \ldots\ldots bNz^{-N}}{1 + a1z^{-1} + \cdots \ldots\ldots\ldots aMz^{-M}} = \frac{(z-z1)(z-z2)\ldots\ldots\ldots\ldots(z-zM)}{(z-p1)(z-p2)\ldots\ldots\ldots\ldots(z-pN)} \qquad (1)$$

Where, transfer function or system function is H(z) and B(z) is the z-transform of the output sequence and A(z) is the z-transform of the input sequence. b0, b1, bN and a1, a2, aM are coefficients. z1, z2 ...zM are called zeros of the transfer function because zeros of the system function are values of z for which H(z)=0. similarly, p1, p2...pM are called poles of the transfer function because these are values of z for which H (z) =infinite. Since initially we are considering only zeros of digital notch filters, so we are neglecting the denominator factors.

Location of zeros is given by $\cos(\omega_o) + j\sin(\omega_o)$

Or $\cos(\omega_o) - j\sin(\omega_o)$,

Where $\omega_o = (\pm)\, 2\Pi\, (f_o/f_s)$

$= (\pm)\, 2\Pi\, (60/200)$

$= (\pm)$ 1.88 radian

$= (\pm)$ 108 degree

So, locations of zeros will be

z1= -0.3090 + j 0.9510

z2= -0.3090 - j0.9510

After putting in equation (1), resulting transfer function will be [6]

$$H(z) = \frac{1 + 0.618z^{-1} + z^{-2}}{2.618} \qquad (2)$$

The transfer function is divided by 2.618 to make DC gain=1(at z=1). pole zero plot of filter with only two zeros and having no poles is given as shown in figure-2.

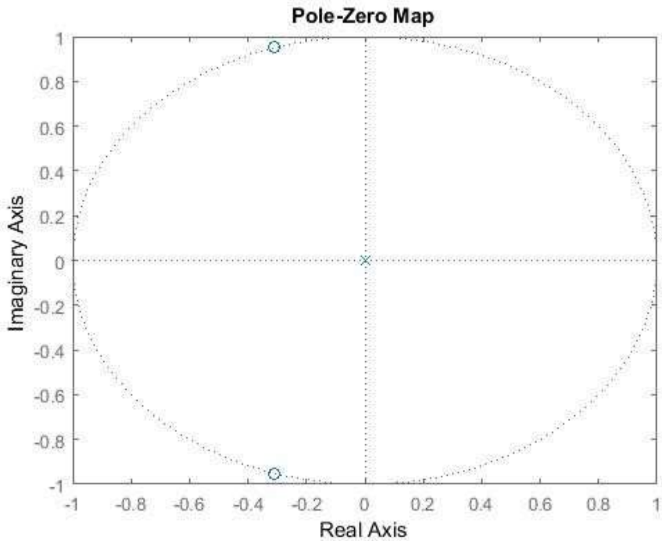


Figure 2: Pole Zero plot of given transfer function

4 Frequency Response

Modern biomedical instruments are designed to handle data with bandwidths from dc up to several hundred cycles per second. Electrical or mechanical filters cannot separate useful signals from the noise when their bandwidth overlaps. Also, the bioelectrical signals often contain components of extremely low frequency. For a faithful reproduction of the signal, the amplifiers must have excellent frequency response (magnitude and phase response) in the sub audio frequency range. It is not desirable to have the frequency response of the amplifiers much above the highest signal frequency. Excessive bandwidth allows passage of noise voltages that tend to change the bioelectric signal [10]. The magnitude and phase response of all zero notch filters with only two zeros is given in figure-3 as shown below.

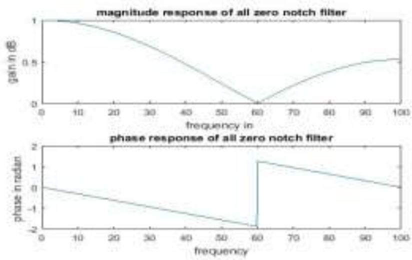


Figure 3: Magnitude and Phase response of all zero-notch filter

So, the comparison between the filtered output with only two zeros and input signal in time domain is shown in figure-4.

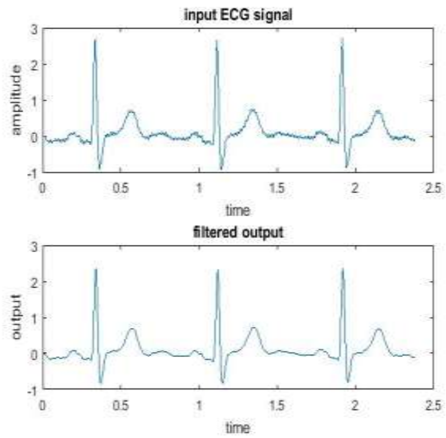


Figure 4: Input ECG signal and filtered output

5 Improvement of Signal to Noise ratio (SNR)

It is the measurement of the amplitude of the variance of the signal relative to the variance of the noise. The higher the SNR, the better you can distinguish your signal from the noise. It is calculated in dB. Mathematically the SNR is [11]

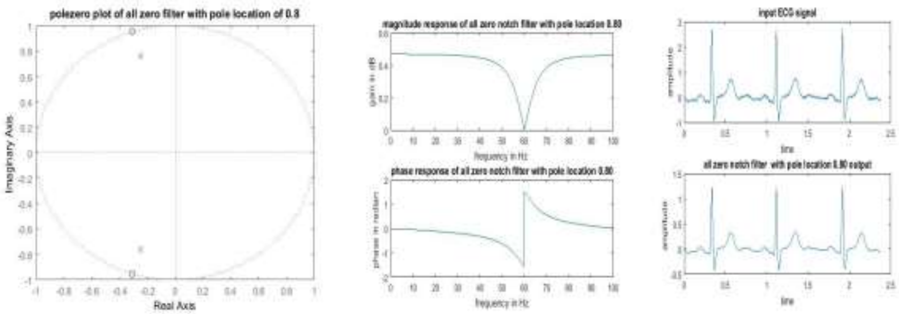
$$SNR = 10*\log(\text{Signal Energy}/\text{Noise Energy}) \qquad (3)$$

5.1 Case-1

When a pole having radius 0.8(p1, p2=0.8*e$^{(+-)j108}$ is added to two zero notch filter, the resulting transfer function becomes [12]

$$H(z) = \frac{1+0.618z^{-1}+z^{-2}}{1+0.4944z^{-1}+0.64z^{-2}} \qquad (4)$$

The corresponding pole-zero plot, magnitude and phase response and comparison of filter output with input signal is shown in Figure-5 respectively



(a) (b) (c)

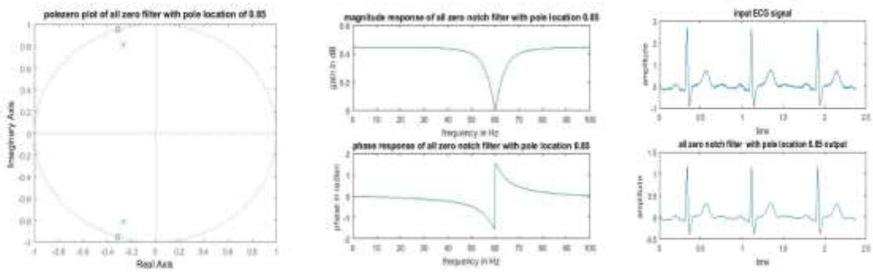
Figure 5: (a) Pole Zero plot with pole location at 0.80 (b) Magnitude and Phase Response of Notch filter for pole at 0.80 (C) Input ECG signal and Output ECG signal after passing through Notch filter

5.2 Case-2

When a pole having radius of 0.85(p1, p2=0.85*e $^{(\pm)\,j108}$ is added to two zero notch filter, the resulting transfer function becomes

$$H(z) = \frac{1+0.618z^{-1}+z^{-2}}{1+0.525z^{-1}+0.722z^{-2}} \qquad (5)$$

The corresponding pole zero plot, magnitude and phase response and comparison of filter output with input signal as shown in Figure.6 as given below.



(a) (b) (c)

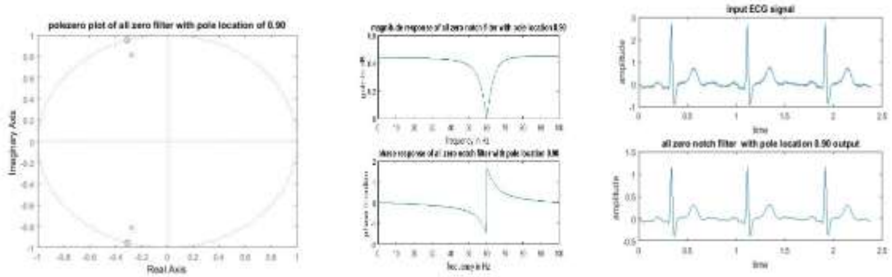
Figure 6: (a) Pole Zero plot with pole location at 0.85 (b) Magnitude and Phase Response of Notch filter for pole at 0.85 (C) Input ECG signal and Output ECG signal after passing through Notch filter

5.3 Case-3

When a pole having radius of 0.90(p1, p2=0.90*e $^{(\pm)\,j108}$ is added to two zero notch filter, the resulting transfer function becomes

$$H(z) = \frac{1+0.618z^{-1}+z^{-2}}{1+0.5562z^{-1}+0.7325z^{-2}} \qquad (6)$$

The corresponding pole zero plot, magnitude and phase response and comparison of filter output with input signal as shown in figure-7



(a) (b) (c)

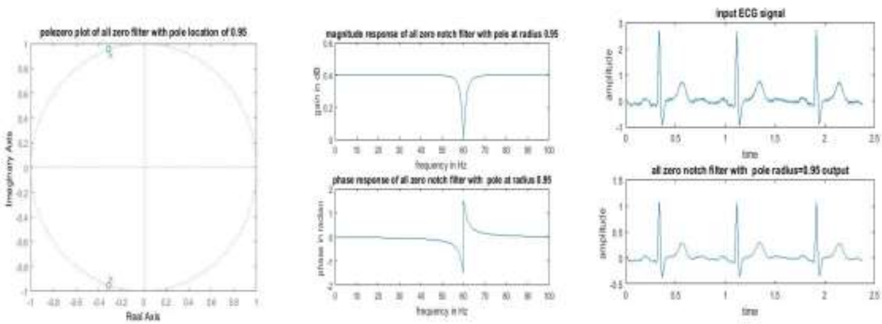
Figure 7: (a) Pole Zero plot with pole location at 0.90 (b) Magnitude and Phase Response of Notch filter for pole at 0.90 (C) Input ECG signal and Output ECG signal after passing through Notch filter

5.4 Case-4

When a pole having radius of 0.95(p1, p2=0.95*e $^{(+-)j108}$ is added to two zero notch filter, the resulting transfer function becomes

$$H(z) = \frac{1+0.618z^{-1}+z^{-2}}{1+0.587z^{-1}+0.90227z^{-2}} \qquad (7)$$

The corresponding pole zero plot, magnitude and phase response and comparison of filter output with input signal is shown in figure 8 as given below.



(a) (b) (c)

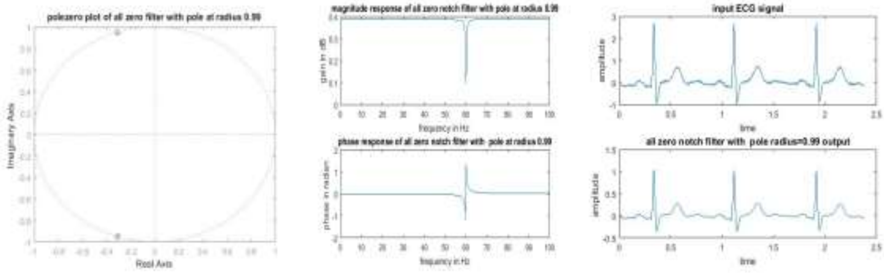
Figure 8: (a) Pole Zero plot with pole location at 0.95 (b) Magnitude and Phase Response of Notch filter for pole at 0.95 (C) Input ECG signal and Output ECG signal after passing through Notch filter

5.5 Case-5

When a pole having radius of 0.99(p1, p2=0.99*e $^{(+-)j108}$ is added to two zero notch filter, the resulting transfer function becomes

$$H(z) = \frac{1+0.618z^{-1}+z^{-2}}{1+0.61185z^{-1}+0.9795z^{-2}} \qquad (8)$$

The corresponding pole zero plot, magnitude and phase response and comparison of filter output with input signal is shown in figure 9 as given below.



(a) (b) (c)

Figure 9: (a) Pole Zero plot with pole location at 0.99 (b) Magnitude and Phase Response of Notch filter for pole at 0.99 (C) Input ECG signal and Output ECG signal after passing through Notch filter

6 Result

Here output of a notch filter with poles at radius 0.99 is considered as a reference signal for the SNR calculations. Noise signal is obtained by subtracting the output of the filter from the given reference signal. Then signal energy and noise energy is calculated by squaring the peak or maximum amplitude. Due to addition of poles with various radius from 0.8 to 0.99, SNR increases and also, we got better magnitude and phase response of the filter [8]. By reducing the sampling frequency from 200Hz, the effect of addition of poles and zeros may affect on the SNR calculation. The variations of SNR with location of pole are shown in the form of a table-1.

Table-1: Variations of location of Pole with SNR Value

Serial No.	**Location of pole with radius r varies from 0.8 to 0.99**	**SNR value in dB**
1	Without pole	8.46
2	0.8	22.31
3	0.85	24.75
4	0.9	27.88
5	0.95	32.36

7 Conclusion

Notch filters having only zeros in transfer function has very wide notch bandwidth and offers more attenuation at adjacent frequencies. Notch filter with poles added at 0<Radius(r) <1 improves the performance by narrowing the notch bandwidth and decreasing attenuation at adjacent frequencies. As the poles move closer to zeros, notch bandwidth decreases and approaches ideal notch filter. Although addition of pole with all zero-filter having radius varies from 0.8 to 0.99 improves SNR, but noise cannot be completely eliminated. Because noise generates from different sources in the form of external noise and internal noise. During removal of power line interference, noise generated from different types of electrodes, electrolytes, electro-magnetic interference and motion artifacts can cause erroneous result. We can get better efficiency, improved accuracy and narrowing notch bandwidth by varying radius of pole from 0.9 to 0.999. To further extend this work we can use different types of notch filter of various order.

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