ISSN Online: 2821-1693

Transactions on Machine Intelligence

Journal Homepage: https://tmachineintelligence.ir/index.php/TMI

An Investigation on the performance of Infinite Impulse Response Filters in Denoising Electrocardiogram Signals

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ARTICLE INFO

Article History:
Received 7 December 2022
Received in revised form
9 January 2023
Accepted 5 March 2023
Available online 6 March 2023

Keywords:
IIR Filter, Butterworth Filter,
Chebyshev Filter, ECG Signal.

ABSTRACT

Electrocardiogram (ECG) signals play a vital role in the clinical assessment of cardiac function, enabling the diagnosis of various heart disorders and the monitoring of treatment outcomes. However, these signals are frequently contaminated by diverse sources of noise, including electromagnetic interference from urban environments (such as 50 Hz powerline noise), muscle activity (electromyographic signals), and even neurological signals. These unwanted signal components, collectively referred to as "noise," can significantly degrade the quality of the ECG waveform, complicating both visual inspection and automated analysis. To ensure the accurate interpretation of ECG recordings, it is essential to employ effective signal processing techniques that can suppress noise while preserving the integrity of diagnostically relevant features. In this study, we investigate and compare the performance of three Infinite Impulse Response (IIR) digital filters: Butterworth, Chebyshev Type I, and Chebyshev Type II. The primary objective is to attenuate the dominant 50 Hz interference commonly observed in urban clinical and research environments. Comprehensive simulations and tests on real ECG signals demonstrate that the Chebyshev Type I filter offers a particularly effective balance between sharp frequency selectivity and minimal signal distortion. Its performance in attenuating noise within both the passband and stopband makes it a favorable choice for preprocessing ECG data, thereby enhancing diagnostic accuracy in biomedical signal analysis applications.

1. INTRODUCTION

In recent research, various innovative approaches have been proposed to enhance the quality of electrocardiogram (ECG) signals by addressing different sources of interference. Mishra et al. (2021) present a denoising method utilizing an S-transform based time–frequency filtering approach, effectively reducing mean square error and improving the signal-to-noise ratio while preserving structural information [1]. Another noteworthy contribution comes from An and Stylios (2020), who focus on motion artefact reduction in wearable electrocardiogram monitoring. Their adaptive filter demonstrates efficacy, particularly when utilizing impedance

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http://dx.doi.org/10.47176/TMI.2023.10

pneumography as a reference input signal, providing valuable insights for improving monitoring accuracy [2]. Furthermore, Patel and Shah (2022) propose a multiband filter for denoising electrocardiogram signals, showcasing effectiveness in mitigating noise and preserving critical cardiac information in the presence of environmental interference. Their research, published in the Serbian Journal of Electrical Engineering, offers a novel perspective on signal processing in ECG applications [3].

In the realm of diaphragmatic electromyography signals, Li et al. (2022) introduce a dual-threshold filter-based denoising method. This innovative approach effectively removes ECG interference, enhancing the applicability of diaphragmatic electromyography signals in scenarios with weak signals. The findings are documented in the Journal of Mechanics in Medicine and Biology [4]. An electrocardiogram (ECG) captures the graphical representation of electrical potential changes arising from the stimulation of the heart muscles. This continuous recording, done on a specially designed paper tape, illustrates the heart's electrical stimulus and the various stages of stimulation through discernible waves. The resulting graph is referred to as an electrocardiogram, a pivotal tool that aids physicians in comprehending the functioning of the heart [5]. Within each ECG graph, three distinct waves are observed: the P-wave signifies the electrical activity of the atria, the QRS complex mirrors the electrical activity of the ventricles, and the T-wave indicates the recovery phase of the ventricles. These ECG signals provide valuable insights into the heart's responses to different stimuli or disturbances. Physicians leverage the characteristics of these signals, influenced by wave frequencies and modes of operation, to model and detect heart disorders and pathologies [6, 7]. To enhance clarity, technical abbreviations will be explained upon initial use. The ECG signal is often intertwined with other biological signals, such as brain signals, muscle electrical activity, and power lines. The analysis of ECG poses challenges due to artifacts, generating noise that complicates the identification of cardiovascular rhythms [8,9]. Ensuring precise analysis and diagnosis necessitates the elimination of unwanted noise and extraneous signals from the ECG.

This study aims to employ straightforward yet effective methods, utilizing three types of second-order IIR filters (Butterworth, Chebyshev type I, and II), to eliminate noise from the heart signal. Subsequently, we will compare the performance of these filters to identify the most effective one.

2. INFINITE IMPULSE RESPONSE FILTERS

IIR filters represent crucial components in Digital Signal Processing, constituting one of the two main types of digital filters employed in DSP applications—the other being FIR filters. Unlike FIR filters, when an impulse function is applied to the input of an IIR filter, the output does not completely decay. Instead, it persists at a finite value continuously. Consequently, the transfer function of these filters comprises an infinite number of elements. Due to this infinite nature, IIR filters cannot be transformed from the convolution of the input into the impulse response. Implementing such a sum of an infinite number of terms at each instant becomes practically unfeasible in a real digital system.

To address this challenge, recursive relationships are employed in constructing digital IIR filters. This implies that the output at any given moment is dependent not only on the current and previous input values but also on the output values calculated and stored in preceding moments. This recursive nature allows for a more manageable implementation in digital systems [10,11]. The general IIR difference equation takes the following form:

$$\sum_{j=0}^{Q} a_l y[n-j] = \sum_{i=0}^{P} b_k x[n-i] \tag{1}$$

A rearranges in this equation so that y[n] is on the left and all of the other terms are on the right results in:

$$\mathrm{y[n]} = \frac{1}{a_0}\left(\sum_{i=0}^{P} b_i x[\mathrm{n-i}] - \sum_{j=1}^{Q} a_j y[\mathrm{n-j}]\right) \tag{2}$$

In other words:

$$y[\mathrm{n}] = \frac{1}{a_0}(\mathrm{b_0 x[n] + b_1 x[n-1] + ... + b}_p \mathrm{x[n-}P] \\ -\mathrm{a_1 y[n-1] - a_2 y[n-2] - ... - a}_Q\mathrm{y[n-Q]}) \quad (3)$$

Figure 1 shows the block diagram of Direct-Form I of equation (3).

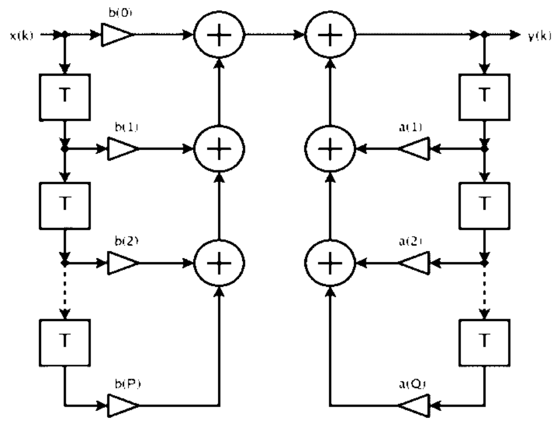

Fig. 1. Direct Form I Structure

To find the transfer function of the filter, we first take the Z-transform of each side of the above equation, where we use the time-shift property to obtain:

$$\sum_{j=0}^{Q} a_j z^{-j} Y(\mathrm{z}) = \sum_{i=0}^{P} b_i z^{-i} X(\mathrm{z}) \quad (4)$$

We define the transfer function to be:

$$H(z) = \frac{Y(z)}{X(z)} = \frac{\sum_{i=0}^{P} b_i z^{-i}}{\sum_{j=0}^{Q} a_j z^{-j}} \quad (5)$$

2.1. Common IIR Filters

The classic IIR filters, which include Butterworth, Chebyshev, elliptic, and Bessel, all come with approximations of ideal filters in a variety of ways. In this discussion, we used the Chebyshev Type I and II and Butterworth filters and compared them to noise removal. The description of the use of any of the filters mentioned in MATLAB software is as follows:

Butterworth filter:

n MATLAB software, the Butterworth filter receives two inputs named, N (the degree of filter) and W (the desired signal frequency range [W1 W2]) and two outputs named, A (denominator coefficients) and B (nominator coefficients) due to the last paragraph. The filter has three modes of high pass, low pass and intermediate pass, which can be changed in the third filter input.

$$[B, A] = butter(N, [W1\ W2], 'ftype') \quad (6)$$

Chebyshev filter type I:

Equation (7) shows the approach of implementing a Chebyshev type I filter in MATLAB software. According to this equation, the Chebyshev type I receives three inputs named, N (the degree of filter), W (the desired signal frequency range [W1 W2]), and R the peak bandwidth to the peak of the signal, which is generally considered to be 0.5 and two outputs named, A (denominator coefficients) and B (nominator coefficients). Similar to the Butterworth filter, this filter has three types of high-pass, low-pass, and intermediate pass, in which the filter mode can be changed in the third input.

$$[B, A] = cheby1(N, R, [W1\ W2], 'ftype'); \tag{7}$$

Chebyshev filter type II:

The Chebyshev type II filter has an approach for implementation in MATLAB software which is shown in equation (8). According to the this equation, this filter receives three inputs named, N (the degree of filter), W (the desired signal frequency range [W1 W2]), and R the peak bandwidth to the peak of the signal, which is generally considered to be 20 and two outputs named, A (denominator coefficients) and B (nominator coefficients).This filter, like the Butterworth filter and Chebyshev type I, has three types of high-pass, low-pass, and intermediate pass, in which the filter mode can be changed in the third input.

$$[B, A] = cheby2(N, R, [W1\ W2], 'ftype'); \tag{8}$$

2.2. The correlation coefficient:

The correlation coefficient serves as a metric for gauging the similarity between a signal and its transmitted counterpart. In essence, it quantifies the strength of the relationship between two signals. In MATLAB, the correlation coefficient can be computed using the corr() function, requiring two comparable signals that are one-dimensional and of equal length. The resulting output from this function is a numerical value falling within the range of 1 to -1. A value closer to one indicates a higher degree of similarity between the two signals. In this study, we applied each of the aforementioned filters to an Electrocardiogram (ECG) signal, which was affected by power line noise. To assess the impact of each filter on signal denoising, we employed the correlation coefficient to measure the similarity between the output of each filter and the noise-free signal. This approach allows us to quantitatively evaluate the effectiveness of each filter in mitigating the impact of noise on the ECG signal.

3. RESULTS AND DISCUSSION

In this section we have provided a brief overview of the results achieved in this research. Figure 2 shows original ECG signal without noise (a), and the next part is the same signal with noise interference (b), the last image is also related to the Fourier transform of the signal affected by noise.

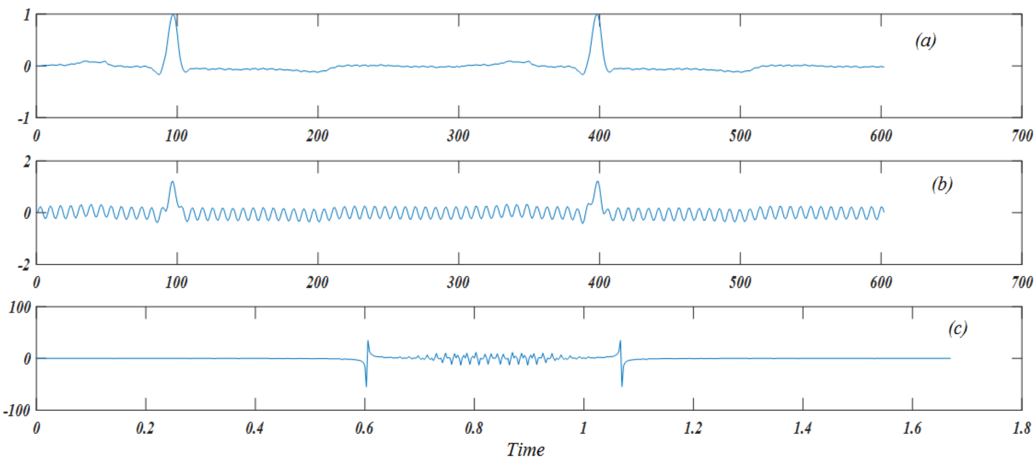

Fig. 2. (a) Main ECG signal (b) Main signal with noise (c) Fast Fourier Transform of (b)

Figure 3 shows impact of a Butterworth filter in denoising an ECG signal. In this figure (a) determines the signal after using Butterworth Filter and a comparison of filter output with main signal (b).

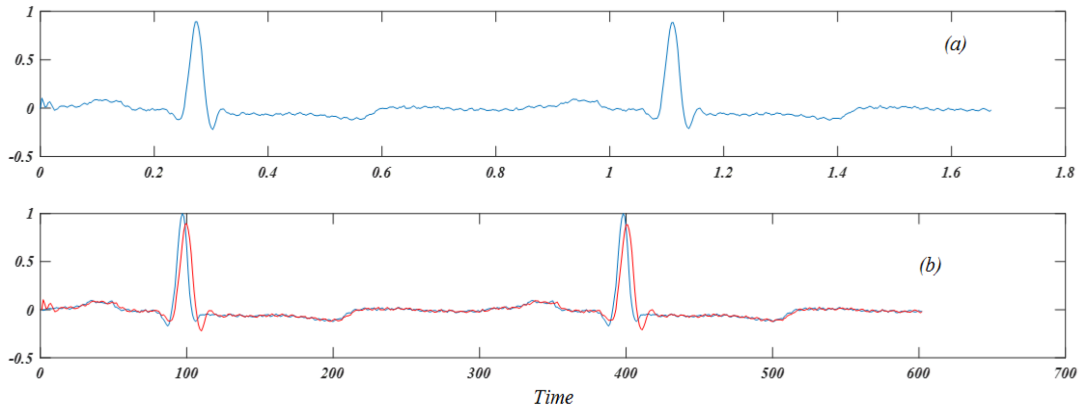

Fig. 3. (a) ECG signal after using Butterworth Filter (**b**) Comparison of filter output with main signal

Figure 4 shows impact of a Chebyshev I filter in denoising an ECG signal. In this figure (a) determines the signal after using Butterworth Filter and a comparison of filter output with main signal (b).

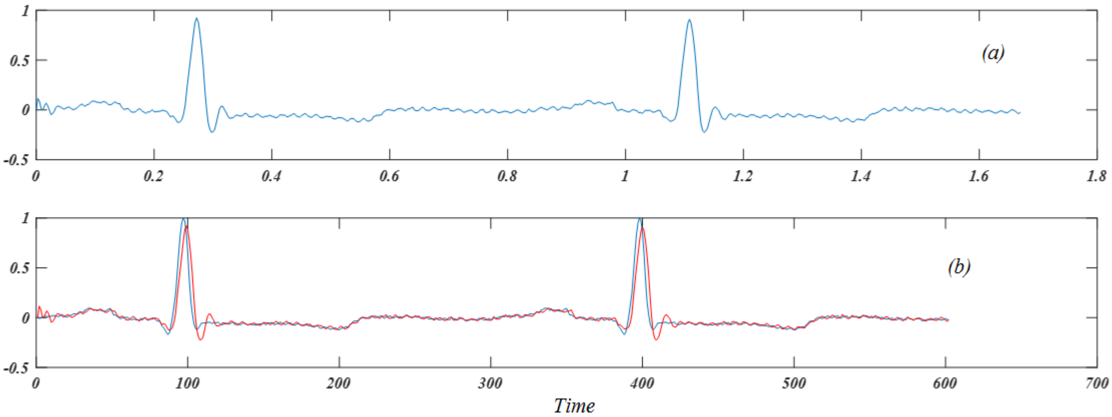

Fig. 4. (a) ECG signal after using Chebyshev I Filter (**b**) Comparison of filter output with main signal

Figure 5 shows impact of a Chebyshev II filter in denoising an ECG signal. In this figure (a) determines the signal after using Butterworth Filter and a comparison of filter output with main signal (b).

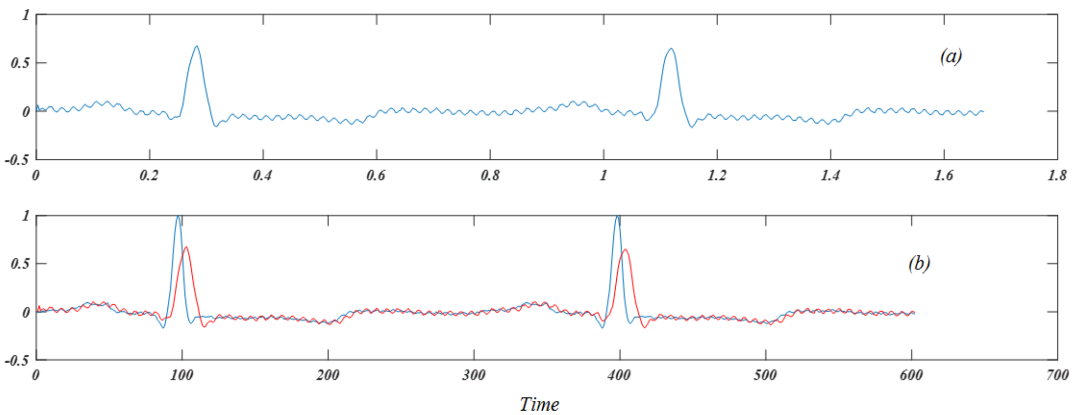

Fig. 5. (a) ECG signal after using Chebyshev II Filter (**b**) Comparison of filter output with main signal

Nowadays, the utilization of digital filters is highly significant and practical. Intermediate and non-intermediate pass filters can be employed to eliminate noise from crucial and functional signals like ECG. The results obtained from these three filters are evaluated by the corr() function in MATLAB to determine their efficiency and recommend the optimal filter for denoising ECG signals in digital signal processing (DSP). To achieve this goal, we computed the correlation coefficients of all the output signals with the primary signal, as demonstrated underneath:

Butter = *0.8269*   cheby1 = *0.8902*   cheby2 = *0.5547*

These results confirm that Chebyshev type I has the best performance in denoising ECG signal from power line noise (50 Hz). It is worth mentioning that the other filters may has better performance in their pass band region, but to evaluate a filter performance, both region of pass band and rejection band.

4. CONCLUSION

In conclusion, the accurate analysis of heart rate signals is essential for meaningful medical diagnoses and treatment assessments. Various factors, including urban vibrations, brain activity, and muscle movements, contribute to the interference known as "noise" in recorded heart rate signals. Such noise can significantly impede the precise detection and diagnosis of primary signals during medical analysis. Given the critical role of Electrocardiogram (ECG) signals in disease diagnosis and treatment effectiveness assessment, the development of effective filters becomes imperative. In this study, we conducted a thorough analysis of three IIR-type digital filters: Butterworth, Chebyshev-I, and Chebyshev-II, with a specific focus on mitigating the impact of 50 Hz urban noise on cardiac signals. Our findings reveal that, among the tested filters, the Chebyshev-I filter emerges as highly effective in reducing noise across both the passband and stopbands of ECG signals. This effectiveness positions the Chebyshev-I filter as a promising tool for enhancing the accuracy of medical analyses relying on ECG signals. As we continue to refine and innovate in signal processing techniques, these insights contribute valuable knowledge towards improving the reliability of heart rate signal analysis in medical applications.

REFERENCES

[1] Mishra, A., Sahu, S., Sharma, R., & Mishra, S. (2021). Denoising of Electrocardiogram Signal Using S-Transform Based Time–Frequency Filtering Approach. Arabian Journal for Science and Engineering, 46, 9515 - 9525. doi.org/10.1007/s13369-021-05333-z.

[2] An, X., & Stylios, G. (2020). Comparison of Motion Artefact Reduction Methods and the Implementation of Adaptive Motion Artefact Reduction in Wearable Electrocardiogram Monitoring. Sensors (Basel, Switzerland), 20. doi.org/10.3390/s20051468.

[3] Patel, V., & Shah, A. (2022). Denoising electrocardiogram signals using multiband filter and its implementation on FPGA. Serbian Journal of Electrical Engineering. doi.org/10.2298/sjee2202115p.

[4] Li, S., Li, Z., Zhang, J., & Zhang, H. (2022). A Denoising Method of Diaphragm Electromyogram Signals Based On Dual-Threshold Filter. Journal of Mechanics in Medicine and Biology. doi.org/10.1142/s0219519422400097.

[5] Beckmann, J. S., Ye, Y. Z., Anderson, P. G., Chen, J., Accavitti, M. A., Tarpey, M. M., & White, C. R. (1994). Extensive nitration of protein tyrosines in human atherosclerosis detected by immunohistochemistry. Biological Chemistry Hoppe-Seyler, 375(2), 81–88. doi:10.1515/bchm3.1994.375.2.81.

[6] Naazneen, M. G., Fathima, S., Mohammadi, S. H., Indikar, S. I. L., Saleem, A., & Jebran, M. (2013). Design and Implementation of ECG monitoring and heart rate measurement system. International Journal of Engineering Science and Innovative Technology (IJESIT), 2(3), 456–465.

[7] Correa, A. G., Laciar, E., Patiño, H. D., & Valentinuzzi, M. E. (2007). Artifact removal from EEG signals using adaptive filters in cascade. Journal of Physics. Conference Series, 90, 012081. doi:10.1088/1742-6596/90/1/012081.

[8] Liu, Y.-L., Chang, N.-C., Hsu, S.-F., Lin, D.-L., & Lin, Y.-D. (2004). An adaptive algorithm for canceling power-line interference in biopotential measurement. Biomedical Engineering: Applications, Basis, and Communications, 16(06), 350–354. doi:10.4015/s1016237204000487.

[9] Adamec, J., & Adamec, R. (2008). ECG Holter: Guide to Electrocardiographic Interpretation. Springer Science & Business Media. doi.org/10.1007/978-0-387-78187-7.

[10] Regalia, P. (2018). Adaptive IIR filtering in signal processing and control. Routledge.

[11] Cuomo, K. M., & Oppenheim, A. V. (1993). Chaotic signals and systems for communications. IEEE International Conference on Acoustics Speech and Signal Processing. Presented at the Proceedings of ICASSP ’93, Minneapolis, MN, USA. doi:10.1109/icassp.1993.319454.