Optimum Digital Filter Design for Removal of Different Noises from Biomedical Signals

Shailu Srivastava and Shruti Jain

Abstract The denoised signal with enhanced quality is utilized for correct analysis of biomedical signal. In real-time applications, these signals are mostly affected by distinct types of artefacts. The objective of this research paper is to design the optimum digital filter for the elimination of noises lies in high- and low-frequency bands. The proposed methodology is implemented using approximations and windowing techniques. The results of frequency responses of both the designed filters are evaluated and compared on the basis of pole–zero plot and gain. It is interpreted from the simulated results that the design technique with the help of Kaiser window results in −61.75 and −56.89 dB for high-frequency and low-frequency signals, respectively, while assuming shape parameter as 0.5. The proposed design method can be used in different digital signal processing applications.

Keywords Digital filters · Low-frequency noise · High-frequency noise · Window technique · Butterworth filter

1 Introduction

Signal processing is performed in most of the systems for biosignal interpretation and analysis [1]. Nowadays, biomedical signal processing has been close towards objective or the quantitative analysis of physiological systems and phenomena through signal evaluation [2]. These signals contain valuable clinical information in real time which is hampered by different noises such as electrode contact noise, instrumental noise, baseline noise, motion artefacts, power line interference and electrosurgical noise [3]. Different types of digital filters are used for the removal of artefacts from signal components. It is very tedious to reduce random noises having fixed coefficients.

S. Srivastava · S. Jain (✉)
JUIT, Solan, Himachal Pradesh, India
e-mail: jain.shruti15@gmail.com

N. Marriwala et al. (eds.), *Mobile Radio Communications and 5G Networks*, Lecture Notes in Networks and Systems 140,
https://doi.org/10.1007/978-981-15-7130-5_30

The situations which include motion of the patient (running or walking), breathing, interplay among the electrodes pores and skin are the reasons of occurrence of low-frequency noises/baseline wandering [4]. The signal gets drifted with a high degree from baseline and is known as baseline wander. The presence of muscle noise is due to high-frequency noise/electromyography (EMG) noise that represents a fast rate trouble in most of the applications, particularly in recordings acquired during exercise, for the reason that low amplitude waveforms may turn out to be absolutely obscured. EMG noise occurs due to the shrinkage of muscles other than the cardiac muscular tissues [3, 4]. The degree of crosstalk is always in proportion to the amount of muscular contraction that takes place either due to the probe quality or movement. The frequency of the EMG noise lies in between 100 and 500 Hz or further taken to the higher frequencies. Muscle noise, baseline wander and 50/60 Hz noise are not always removed by using narrowband filtering. This affords a much extra filtering trouble because of the spectral content of muscle activity.

To remove the artefacts from the biomedical signals, different techniques were proposed in the last twenty years. To get the important data which is present in a specific frequency range, digital filters may be used [5]. In general, these techniques can be categorized into adaptive and non-adaptive filtering [6]. The non-adaptive filtering consists of infinite impulse response (IIR) filter, finite impulse response (FIR) filter and the notch filter. The FIR filters are considered for removing the noise and spectral effectively from the biomedical signal. An FIR filter includes multipliers, delays and adders to get the output [7–9]. As the order of the filter increases, there is an increase in the execution time and complexity. Theoretical and experimental results using the windowing technique are almost similar due to the availability of a well-structured equation [10].

In this paper, authors have studied distinct research papers on specific filtering strategies [11]. Alarcon et al. implemented algorithms for high-pass and low-pass three-pole recursive Butterworth filters at particular cut-off frequency [12]. Gaikwad and Chavan suggested that digital IIR filtering approach is best suited for the removal of high-frequency noise from ECG Signal [13]. Rahman et al. [14] remove the baseline wandering by using the wandering path finding algorithm. Authors in [15] worked on FPGA-based FIR low-pass filter for the removal of EMG noise from electrocardiogram. Authors in [16] discussed the various noises present in biomedical signals and different techniques to remove these noises.

The main utility of a filter is to discard unnecessary signal components [17, 18], like baseline wander noise or EMG noise. The main aim of this research work is to design an optimum digital filter for removal of noises lies in high- and low-frequency bands. For the smoother transitions, better gain and ability to control the ripple content, authors have implemented different digital filters using LabVIEW. The main requirement of this method is to maintain physiological characteristics after denoising. Gain (in dB) is calculated for different digital filters. The pole–zero plot and frequency responses of both the filters were also analysed.

The rest of the paper is structured as follows: Sect. 2 explains the methodology segment, Sect. 3 explains the results and discussion which are followed by the conclusion and future scope in Sect. 4.

2 Methodology

Various types of filters are categorized primarily based on signal processing, elements type, construction filters, impulse response and frequency range. The transfer function for a time-invariant, linear digital filter known as the recursive filter can be expressed in z- domain and is represented by Eq. (1).

$$H(z) = \frac{B(z)}{A(z)} = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2} + \ldots b_N z^{-N}}{1 + a_1 z^{-1} + a_2 z^{-2} + \ldots a_M z^{-N}} \tag{1}$$

where $a_0, a_1, \ldots a_n$ and $b_0, b_1, \ldots b_n$ are filter coefficients. If the denominator in Eq. (1) is made equal to unity (no feedback), then the filter will act as an FIR filter [6]. The impulse response is a measurement of how a filter will respond to the delta function and is expressed by Eq. (2).

$$\delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases} \tag{2}$$

Window functions are a category of time-domain functions. Gibb's oscillations are decreased by using a suitable window function [1, 2]. Window functions $[w(nT_s)]$ are used to restrict the impulse response $[h(nT_s)]$ with certain value. $H(z)$ is the z transform of $[h(nT_s)]$ expressed by Eq. (3), $W(z)$ is the z transform of $w(nT_s)$ expressed by Eq. (4), and $H_{\mathrm{w}}(z)$ is the z transform of $[w(nT_{\mathrm{s}})h(nT_{\mathrm{s}})]$ expressed by Eq. (5).

$$H(z) = \sum_{n=-\infty}^{\infty} h(n\,T_s)\, z^{-n} \tag{3}$$

$$W(z) = \sum_{n=-\infty}^{\infty} w(n\,T_s)\, z^{-n} \tag{4}$$

$$H_w(z) = \sum_{n=-\infty}^{\infty} [w(n\,T_s).\, h(n\,T_s)]\, z^{-n} \tag{5}$$

Different filtering approaches are implemented for denoising of the different noises from biomedical signals. Initial step is the identification of noises present in the signal followed by the selection of the filter. Selection of optimal filter is a challenging task as in literature there are two types of filter IIR and FIR, and both have its benefits and downsides. In this paper, authors have stressed on FIR filter using windowing technique and IIR using approximate filter. When a digital FIR filter is designed using window techniques, it is essential to specify window function and the order of the filter as shown in Fig. 1. Gain (in dB) is calculated for different

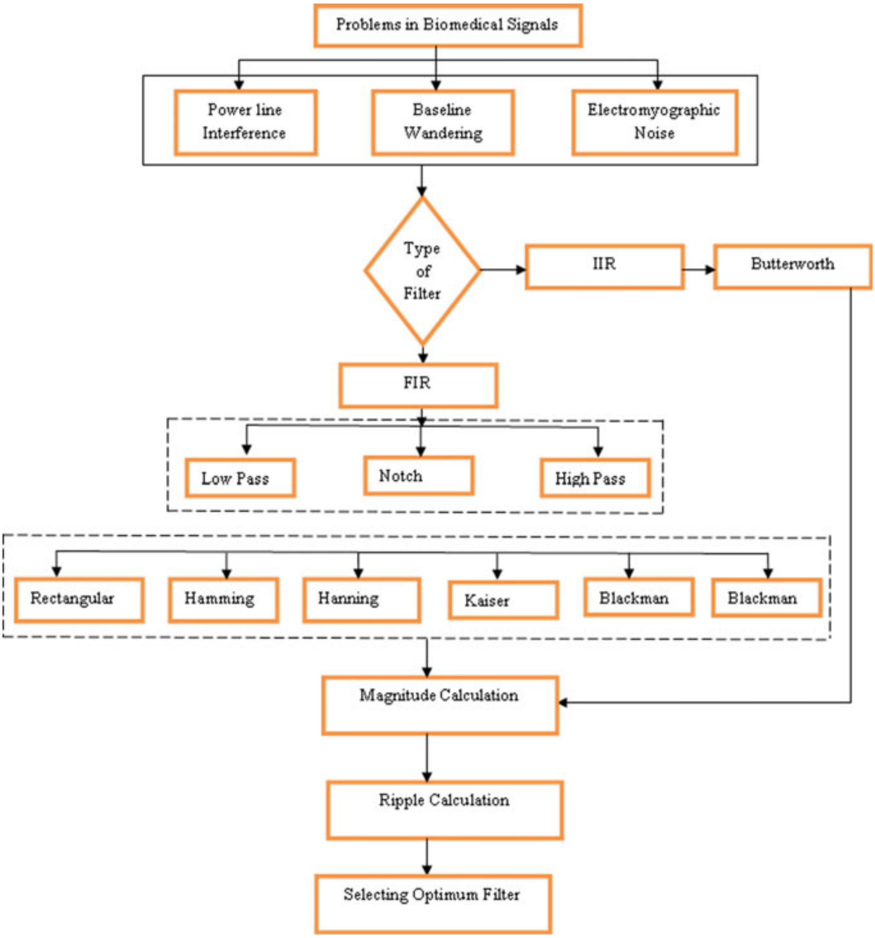

Fig. 1 Filter design steps

digital filters. The pole–zero plot and frequency responses of both filters were also analysed.

The fallacious electrodes placing, patient's motion and respiration (breathing) are the foremost reason of baseline wandering. The baseline signal is a low-frequency signal, with a cut-off frequency of 0.5 Hz FIR high-pass zero phase filters is used for the removal of the low-frequency noise from the biomedical signal [4–6]. Likewise for the removal of the high-frequency signal, low-pass filter with cut-off frequency of 100 Hz is designed.

3 Results and Discussion

There are some random noises such as high-frequency and low-frequency noises present in the biomedical signal. To remove these noises, optimum digital filters were designed using FIR and IIR filtering techniques. FIR and IIR filters are designed using different windowing techniques and approximate techniques, respectively. All the simulation was carried out in Intel 2.4 GHz, 64-bit operating system using LabVIEW and MATLAB software.

Removal of low-frequency noises: The high-pass FIR and IIR filter with cut-off frequency 0.5 Hz are designed (as shown in Fig. 2) to eliminate the low-frequency noises; this helps in removing the signal component of frequency beyond 0.5 Hz.

Table 1 tabulates the effect of order on gain using Butterworth approximate filtering (for IIR).

The gain of −36.53 dB is evaluated for the designed filter of order 2. It is observed that there is a sharp transition from stopband to passband. The pole–zero plot of the designed filter is also studied which is shown in Fig. 3.

The pole and zero both lie on the unit circle (as shown in Fig. 3) that signifies the filter is stable but the impulse response is infinite (as shown in Fig. 4) which is difficult to handle.

To overcome the problem of infinite response of IIR filter, FIR filters using different windows, namely Kaiser, Hamming, Hanning, Blackman, Rectangular and Gaussian are considered [6, 18]. Among various filters, Kaiser window shows the remarkable results. Kaiser window function is expressed by Eq. (6).

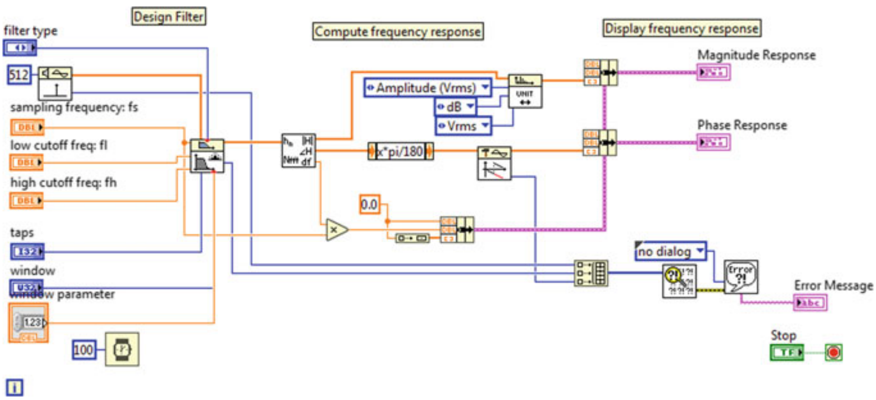

Fig. 2 Implementation of digital filter using LabVIEW

Table 1 Effect of order on gain for Butterworth HPF

Order	Gain (dB)
1	−18.33
2	−36.53

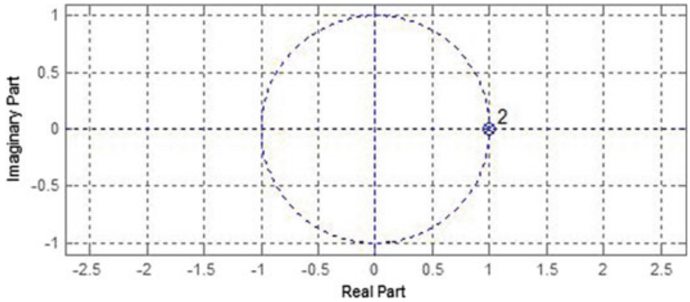

Fig. 3 Pole–zero plot of Butterworth high-pass filter of order 2

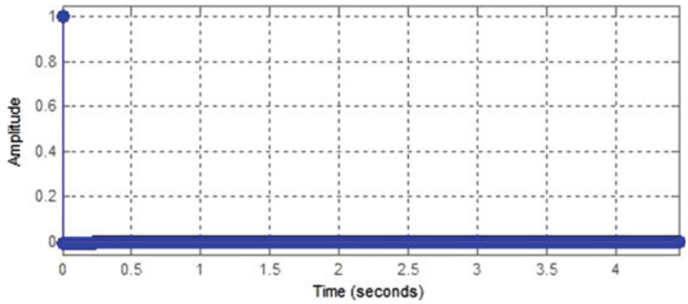

Fig. 4 Impulse response of Butterworth high-pass filter

$$W_k\,(n\,T_s) = \begin{cases} \dfrac{F_o\,(\beta)}{F_o\,(\alpha)} & -\left(\dfrac{N-1}{2}\right) \le n \le \left(\dfrac{N-1}{2}\right) \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

where $F_0(\beta)$ and $F_0(\alpha)$ are the zeroth-order Bessel function of the first kind which is expressed by Eqs. (7) and (8), respectively. In Eqs, $\angle k$ represents factorial of k.

$$F_o\,(\beta) = 1 + \sum_{k=1}^{\infty}\left[\frac{1}{\angle k}\left(\frac{\beta}{2}\right)^k\right]^2 \tag{7}$$

$$F_o\,(\alpha) = 1 + \sum_{k=1}^{\infty}\left[\frac{1}{\angle k}\left(\frac{\alpha}{2}\right)^k\right]^2 \tag{8}$$

α is an independent parameter, and β is a dependent parameter which depends upon α and is expressed by Eq. (9).

$$\beta = \alpha\sqrt{1 - \left(\frac{2\,n}{N-1}\right)} \tag{9}$$

The ripples found in the window can be removed by varying the shape parameter (β). The effect of β on Kaiser window is tabulated in Table 2.

The effect of odd and even order of filters using windowing technique (for FIR) on gain has been studied, and the results are tabulated in Tables 3 and 4, respectively. If the number of taps is odd, then the delay of the filter is an integer number of samples, which is desirable for some applications while if the number is even, then it leads to half-sample delay.

From Table 4, it is interpreted that for odd number order, the gain value decreases, but the transition is sharper for a higher-order filter which is desirable for some applications. From the results, it is interpreted that for linear phase FIR filter, the order of the filter should be odd. Figures 5 and 6 represent the impulse response and pole–zero plot of FIR high-pass filter, respectively, of order 11. It is interpreted that if the length of the impulse response is even, anti-symmetric and has zero at $z = 1$, it represents that the filter is of Type 4 and is best suited for the high-pass filtering.

From all the simulated results, it is analysed that Kaiser window (shown in Fig. 7) yields better results in comparison with other methods because of its sharp transition and better gain value.

The main reason for analysing any filter using windowing technique is its simplicity of design, and the design method is very well understood with basic DSP knowledge.

Removal of EMG/high-frequency noises: The low-pass IIR and FIR filter with cut-off frequency 100 Hz are designed and simulated. For the Butterworth IIR filter of

Table 2 Effect of β on Kaiser window HPF

β	Gain (dB)
0.5	−2.98
1	−2.79
2	−2.33
3	−1.97
4	−1.72
5	−1.539
6	−1.4

Table 3 Effect of even order on gain for HPF Kaiser window

Order	Gain (dB)
50	−0.45
100	−0.894
150	−1.39
200	−1.88
250	−2.409
300	−2.98

Table 4 Effect of odd order on gain for HPF Kaiser window

Order	Gain (dB)
11	−56.89
51	−44.13
101	−38.31
201	−32.48
251	−30.64
301	−29.16

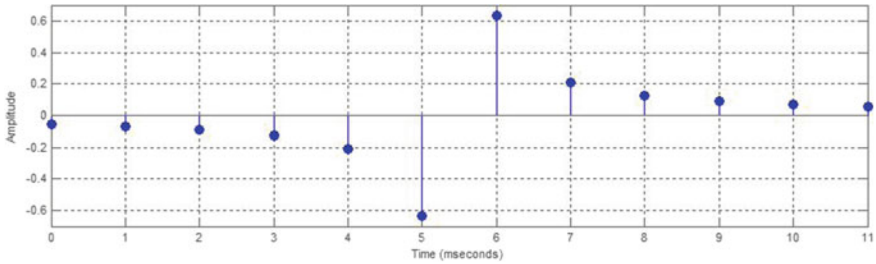

Fig. 5 Impulse response of FIR HPF of order 11

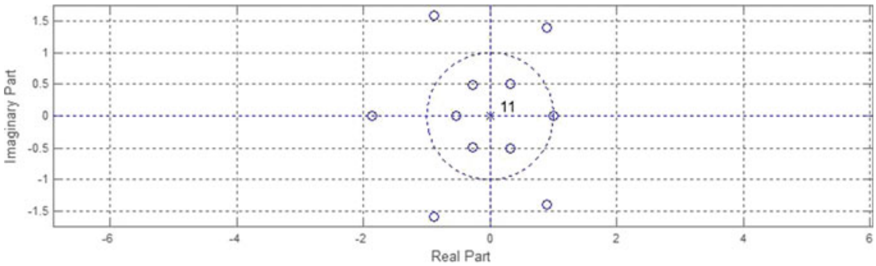

Fig. 6 Pole–zero plot of FIR HPF of order 11

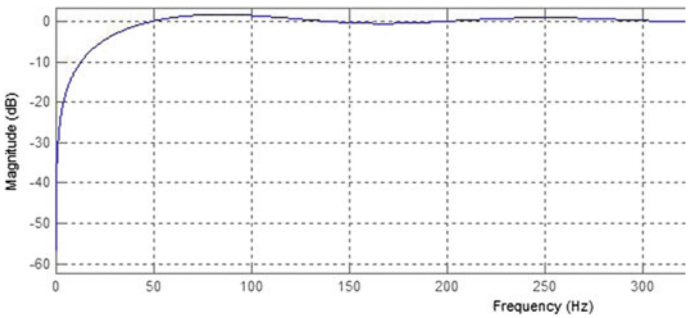

Fig. 7 FIR Filter design at 0.5 Hz using Kaiser window

order 2, it is interpreted that the frequency response is not good because the transition is very poor as shown in Fig. 8.

The pole–zero plot of the filter is also studied as shown in Fig. 9 which illustrates that the pole and zero both lie inside the unit circle that signifies the filter is stable but the impulse response is infinite which is difficult to handle. To overcome this problem, FIR filters using different window techniques are realized, and the results are tabulated in Table 5.

The choice of the window depends on the requirement like characteristics of noise, region of transition and the number of coefficients required. For the different windows, the Blackman windowing technique delivers significant results but have some limitations like large passband width (frequency of 135 Hz), while for the

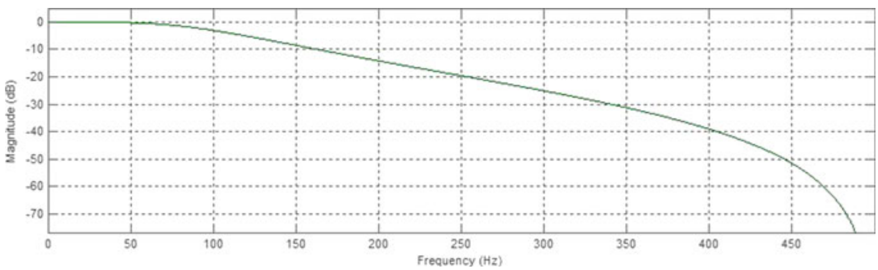

Fig. 8 Frequency response of Butterworth low-pass filter

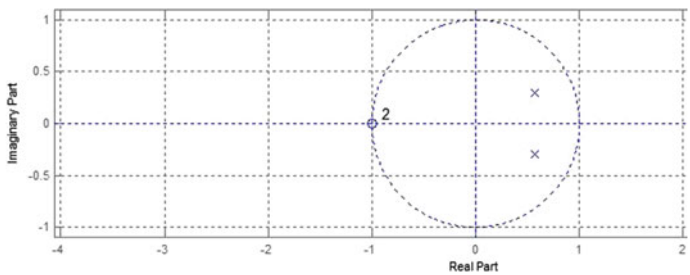

Fig. 9 Pole–zero plot of Butterworth low-pass filter of order 2

Table 5 Effect of gain on different window using LPF

Window	Gain (dB)
Hamming	−80
Hanning	−79.59
Kaiser	−61.75
Blackman	−108.21
Rectangular	−60.28

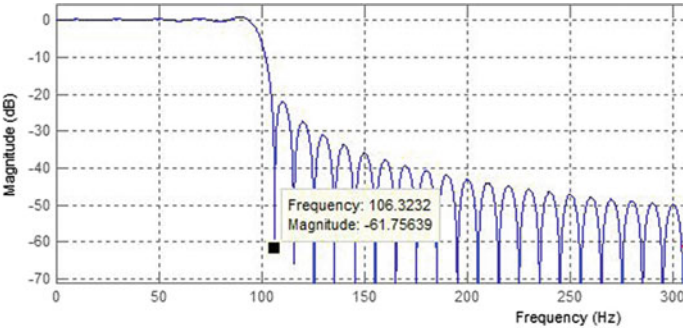

Fig. 10 Frequency response of low-pass FIR filter using Kaiser window

Kaiser window it is observed that the passband width possesses better gain as shown in Fig. 10.

From the frequency response of low-pass Kaiser window filter, it is observed that the gain is more in comparison with other window method as no ripples are found in the passband.

4 Conclusion

In this paper, optimum digital filtering techniques are designed to eliminate different noises that are propagating in the biomedical signal. This research paper carried out the analysis of various filtering methods and simulating in LabVIEW and MATLAB. For IIR Butterworth HPF of order 2, the gain of −36.53 dB is evaluated which shows a sharp transition but the main problem associated with the IIR filtering is its infinite impulse response nature. To overcome this problem, the FIR filter is designed. It is observed that on increasing the order of the filter from 50 to 300, the gain value changes from −0.45 to −2.98 dB. For order eleven, FIR high-pass filter, the value of gain is around −56.89 dB. The low-pass FIR filters are designed for the removal of high-frequency noises that results in −61.75 dB of gain. It is analysed that the FIR filters are best suited for the removal of noises from any biomedical signals because of its finite impulse response and no recursion which is mainly found in the IIR filtering. The Kaiser window is best suited with the appropriate value of β for the removal of different noises because of its better magnitude value and sharp transition from passband to stopband. In future, authors will try to filter the biomedical signals with the help of field-programmable gate array (FPGA).

References

1. Manolakis D, Proakis GJ. Digital signal processing principles, algorithms, and applications, 4th edn. Northeastern University Boston College
2. Jackson LB (2013) Digital filters and signal processing with MATLAB exercises, 3rd edn. Springer Science & Business Media
3. Prashar N, Dogra J, Sood M, Jain S (2018) Removal of electromyography noise from ECG for high performance biomedical systems. Netw Biol 8(1):12–24
4. Prashar N, Jain S, Sood M, Dogra J (2017) Review of biomedical system for high performance applications. In: 4th IEEE International conference on signal processing and control (ISPCC 2017), Jaypee University of Information technology, Waknaghat, Solan, HP, India, pp 300–304, 21–23 Sept 2017
5. Kirti, Sohal H, Jain S (2019) FPGA implementation of power-efficient ECG pre-processing block. Int J Recent Technol Eng 8(1):2899–2904
6. Prashar N, Sood M, Jain S (2019) Design and performance analysis of cascade digital filter for ECG signal processing. Int J Innov Technol Exploring Eng 8(8):2659–2665
7. Pun CKS, Chan SC, Yeung KS, Ho KL (2002) On the design and implementation of FIR and IIR digital filters with variable frequency characteristics. IEEE Trans Circ Syst—II: Analog Digital Signal Proc 49(11):689–703
8. Barnela M, Kumar S, Kaushik A, Satvika (2014) Implementation and Performance Estimation of FIR Digital Filters using MATLAB Simulink Int J Eng Adv Technol 3(5):62–65
9. Wang X, Meng X, He Y (2006) A novel neural networks-based approach for designing FIR filters. In: Proceedings of the 6th world congress on intelligent control and automation, 21–23 June 2006, Dalian, China, pp 4029–4032
10. Schaumann R, Xiao H, Mac VV (2009) Design of analog filters, 2nd edn. The Oxford Series in Electrical and Computer Engineering
11. Rahul (2019) Signal processing techniques for removing noise from ECG signals. J Biomed Eng Res 1–9
12. Alarcon G, Guy CN, Binnie CD (2000) A simple algorithm for a digital three pole Butterworth filter of arbitrary cut-off frequency: application to digital electroencephalography. J Neurosci Methods 104(1):35–44
13. Gaikward KM, Chavan MS (2014) Removal of high frequency noise from ECG signal using digital IIR butterworth filter. IEEE Glob Conf Wireless Comput Netw (GCWCN) 2014 121–124
14. Rahman MA, Milu1 MMH, Anjum A, Khanam F, Ahmad M (2017) Baseline wandering removal from ECG signal by wandering path finding algorithm. In: 3rd International conference on electrical information and communication technology (EICT), 7–9 Dec 2017
15. Bhaskara PC, Uplaneb MD (2016) High frequency electromyogram noise removal from electrocardiogram using FIR low pass filter based on FPGA. Global colloquium in recent advancement and effectual researches in engineering, science and technology (RAEREST 2016) pp 497–504
16. Aswathy V, Soniy P. Noise analysis and different denoising techniques of ECG signal—a survey. IOSR J Electron Commun Eng (IOSR-JECE) pp 40–44
17. Bhogeshwar SS, Soni MK, Bansal D (2014) Design of simulink model to denoise ECG signal using various IIR and FIR filters. In: 2014 international conference on reliability, optimization and information technology—ICROIT 2014. India. 6–8 Feb 2014, pp 477–483
18. Subhadeep C (2013) Advantages of Blackman window over hamming window method for designing FIR filter. Int J Comput Sci Eng Technol 4(8):1181–1189