7.2 nW 68 dB DR Fourth Order Self-compensated Low Pass Filter for Portable ECG Application

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Abstract This paper describes the designing of a fourth order low-pass filter (LPF) for portable ECG application. The proposed filter is designed by cascading one P-biquad and one N-biquad to form a fourth order filter. It is self-compensated and provides a 0 dB gain. It also acquires the same input and output common mode voltages, which helps to produce higher order filters. It consumes power of 7.2 nW with a supply voltage of 1.2 V. Dynamic range of 68.1 dB with noise of 61.2 µVrms is obtained. The proposed filter is designed for a cut-off frequency of 230 Hz, suitable for ECG application. With 100 Hz frequency and 100 mVpp ac amplitude, HD3 of 71 dB is achieved. The circuit is simulated in cadence software using Silterra 130 nm CMOS technology. Compared with other state-of-the-art designs, this novel LPF provides the largest dynamic range and the best figure of merit (FOM).

Keywords: low-pass, ECG, self-compensated, fourth order, cut-off frequency.

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1. Introduction

Biomedical field is one of the most vigorously developing research areas in analog integrated circuit design [1]. There has been a growing demand for low-noise and ultra-low power, miniature biomedical acquisition devices, which has necessitated extensive research in the design of portable biomedical devices for health monitoring and diagnosis of different diseases in human body, such as heart diseases and neural modulation [2]. Different analog integrated circuits have been designed for processing physiological signals such as electrocardiogram (ECG), electroencephalogram (EEG), and electromyogram (EMG) [3–5]. Figure 1 shows different amplitude and frequency ranges of various physiological signals occurring in human body. Figure 2 shows the block diagram of portable ECG detection system.

In ECG detection system, signal from the human body is sensed by an electrode, which is converted into electrical signal. This electrical signal is passed through a low noise amplifier (LNA) having gain between 10–20 as these physiological signals are very weak, and is passed through a low-pass filter (LPF) to filter the out-of-band noise and then through an analog-to-digital converter (ADC) for further processing.

Amplitude of ECG signal varies between 0.05–4 mV.
with a frequency range up to 250 Hz [6]. When considering the amplitude variation of the ECG signal, the overall system requires a dynamic range of greater than 44 dB with an adjustable cut-off frequency 100–250 Hz depending upon the targeted PQRST wave. High frequency-QRS (HF-QRS) frequency range is strictly limited to 250 Hz, as ECG measured at higher frequencies is influenced by rapidly increasing noise and artifacts. HF-QRS is analyzed with the hope that additional features seen in the QRS complex would provide information enhancing the diagnostic value of the ECG, [7–9]. This LPF is the most critical block because the accuracy of the system depends on it. For portable system, designing LPF with very low frequency is not an easy task, especially for fully integrated circuit design. It required very high resistor and capacitor values to maintain this very low frequency and simultaneously maintain the performance characteristics. This low frequency can be achieved by using an active block which can easily replace these high valued resistor and capacitor. One choice is to use continuous time operational transconductance amplifier (OTA) and capacitor having very low transconductance (Gm) that can determine the very low cut-off frequency. Several research articles have discussed the use of OTA for designing low Gm and thus low cut-off frequency [10–12], but the issue of using OTA-C filter is that it requires extra linearization techniques to maintain the linearity of OTA, because the linearity of OTA is poor. Thus large numbers of transistors are required in designing of OTA-C filter. For portable devices, the circuit should have fewer components to make the circuit compact, and low battery voltage for size and weight considerations. Power consumption should also be low so that these portable and implanted devices can be used for a prolonged period of time. Recently, transistorized filter are being designed which can replace the transconductor with a single MOS transistor [11, 13, 14]. This paper discusses the designing of a transistorized LPF that helps to reduce the number of components and simultaneously maintains the performance characteristics of the system. Low noise, high linearity, high dynamic range, low supply voltage with low power consumption are major issues in designing a LPF for portable ECG system. Transistors in the LPF are kept in sub-threshold mode of operation to reduce the power consumption of the circuit. It consumes 7.2 nW power with a supply voltage of 1.2 V and provides a DR of 68.1 dB with a third order harmonic distortion (HD3) of 71 dB at an amplitude of 100 mVpp and frequency of 100 Hz, while 40 dB total harmonic distortion (THD) is obtained at 220 mVp. Input referred noise of 82 µV/√Hz equal to 61.2 µVrms is obtained. This filter is designed for cut-off frequency of 230 Hz, which is suitable for ECG application.

2. Proposed Low-pass filter

Figure 3 shows the designed structure of a N-biquad LPF and Fig. 4 shows its equivalent circuit. Input applied to the gate of NMOS is the N–biquad and vice versa. It consists of three MOS transistors (M1–M3) with two current sources and two capacitors (C1 and C2). Transistors M1 and M2 are coupled together through their sources that form a source coupled transistor (gm1). Transistor M3 provides a negative feedback and its output is connected to the negative input of gm1. Current sources Ib in each branch of the N-biquad are equal and are provided by simple current mirror. Circuit is operated in sub-threshold region with a biasing current of 0.75 nA and supply voltage of 1.2 V. The supply voltage required by the circuit is \( VDD = V_{in} + V_{gsn} + 2 V_{gsp} \), where \( V_{in} \) is the input voltage, and \( V_{gsn} \) and \( V_{gsp} \) are the gates to

![Fig. 3 N-biquad LPF.](image)

![Fig. 4 Equivalent circuit of biquad LPF.](image)
source voltage of n and p transistors, respectively. The LPF is designed by cascading one N-biquad and one P-biquad to form a fourth order filter. It is self-compensated and provides 0 dB gain. Normally, in an N-well process PMOS, transistors are connected to their sources and are free from body effect while NMOS transistors are connected to ground and are affected by their bulks, thus having bulk-induced pass-band attenuation. Both N and P biquads have NMOS transistors in their circuits. Both biquads are affected by their bulks but in opposite direction, which cancels the effect of each other and makes the circuit self-compensating and thus provides 0 dB pass-band gain.

Transfer function of the biquad LPF is given in equation (1) below:

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{gm_1 gm_2 C_1 C_2}{s^2 + s \frac{gm_1 gm_2}{C_1 C_2}} + gm_1 gm_2 C_1 C_2.
\]  

(1)

The above transfer function can easily be applied to cascade and design higher order filter. The cut-off frequency \(\omega_0\) and qualify factor \(Q\) are \(\frac{gm_1 gm_2 C_1 C_2}{ gm_1 C_1 + gm_2 C_2}\) and \(\frac{gm_1 gm_2 C_1 C_2}{ gm_1 C_1 + gm_2 C_2}\), respectively.

From Fig. 4, it can be seen that the source coupled transistors that is equivalent to a transconductor \((gm_1)\) can cause non-linearity, which will produce distortion at the output. This distortion can be suppressed by the global feedback present in the circuit. Output of \(gm_2\) is fed back to the input of \(gm_1\) and thus forms a global feedback while the output of \(gm_2\) is also provided to its negative input forming a local feedback. Both the local feedback and global feedback help to suppress the distortion and achieve HD3 of 68 dB. The capacitor values are set in such a way that they produce a flat pass-band response and the required cut-off frequency suitable for ECG application.

The proposed fourth order LPF is designed to provide a cut-off frequency of 230 Hz. It consumes power of 7.2 nW with a supply voltage of 1.2 V. It provides HD3 of 71 dB with an input signal of 100 mVpp and frequency of 100 Hz. Its input referred noise is 61.2 µVrms that provides a DR of 68.1 dB. The circuit is simulated in Cadence software using Silterra 130 nm CMOS technology. Fully differential structure of the N-biquad is shown in Fig. 5. The macro-models for N biquad and P-biquad are shown in Fig. 6, while the transfer functions including the bulk effect are given in equations (2) and (3), respectively. Both of these equations show that the gain is affected by the bulk but in opposite direction, which provides a flat 0 dB gain without using any compensation circuitry.

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{gm_1 gm_2}{ s^2 + s \frac{gm_1}{ C_1} + \frac{gm_2}{ C_2}(1 + gm_1 + gm_2)}
\]  

(2)

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{gm_2 gm_4}{ s^2 + s \frac{gm_1}{ C_1} + \frac{gm_2}{ C_2}(1 + gm_1 + gm_2)}
\]  

(3)

where;

\(gm_i = gm_i + gm_{bi}\).

From equations 2 and 3, the pass-band gains for N-biquad and P-biquad are \(\frac{gm_1}{ gm_1}\) and \(\frac{gm_2}{ gm_2}\), respectively, showing that the body effect cannot be neutralized within a single biquad, but by cascading both N-biquad and P-biquad together, the bulk effect is cancelled out and 0 dB pass-
band gain is achieved.

3. Simulation Results

The fourth order LPF designed above is simulated in CADENCE environment using Silterra 130 nm CMOS process. The graphs are then plotted using MATLAB with the help of CSV file generated in cadence. Frequency response, transient response, THD, noise analysis and power consumption are calculated and simulated, which are discussed in this section.

3.1 Frequency response of LPF

Frequency response of the fourth order LPF is shown in Fig. 7. The cut-off frequency obtained is 230 Hz with 0 dB pass-band gain obtained by cascading both N-biquad and P-biquad together. By cascading, attenuation due to bulk effect is neutralized and the circuit becomes self-compensated without the use of any additional compensation circuitry. Maximally flat pass-band response is obtained. This 230 Hz frequency is achieved by selecting appropriate value for the capacitors, which plays an important role in LPF design. The values of C1 and C2 are 4 pF and 10 fF for P-biquad while the respective values for N-biquad are 2.2 pF and 10 fF.

3.2 Total Harmonic distortion

LPF consists of one global feedback from out of gm2 to the input of gm1 and a local feedback from the output of gm2 to the input of gm1. This local and global feedback helps in reducing the non-linearity and improves the linear range of the circuit [15]. Figure 8 shows the plot of total harmonic distortion simulated with an input signal of 100 mVpp and frequency of 100 Hz. Third order distortion is 71 dB while the second order harmonics are suppressed due to the differential nature of the structure.

3.3 Transient response

Input signal of 100 mVpp is applied at the input of the LPF. The input and output responses of the filter at 50 Hz frequency is shown in Fig. 9.

3.4 Noise Analysis

Figure 10 shows the integrated noise of the LPF. Three MOS transistors and two current sources are the main components contributing to noise. Sizes of the transistors, especially the lengths, are kept larger to reduce the
channel length modulation effect and to reduce the flicker noise that is dominant at low frequencies. The noise contribution of each component is shown in Table 1, while the integrated noise is 8.1 µV/√Hz = 61.2 µVrms.

### Table 1 Percentage of noise contribution.

| Components | N-biquad | P-biquad |
|------------|----------|----------|
| M1 (%)     | 5.47     | 6.50     |
| M2 (%)     | 7.43     | 5.72     |
| M3 (%)     | 20.48    | 1.89     |
| \(I_{bp}\) (%) | 55.33 | 58.65 |
| \(I_{bn}\) (%) | 11.29 | 27.24 |
| Simulated IRN(µVrms) | 55.11 | 59.42 |

#### 3.5 Power consumption

The fully differential LPF designed in this study has two current sources in one biquad, and each branch consists of 0.75 nW of power with total current in the circuit of 6.01 nA, while the supply voltage used is 1.2 V. The total power consumed by the circuit is 7.2 nW.

#### 4. Fourth order LPF and its application to ECG systems

Fourth order LPF is designed by cascading N-biquad and P-biquad together. First stage of the filter is P-biquad because it provides higher pass-band gain and reduces the noise in the circuit. The second stage is the N-biquad. The same input and output common mode voltages are obtained that helps to cascade and obtain higher order filters [16]. The desired cut-off frequency is obtained by adjusting the values of the capacitors. A flat pass-band response is obtained by cascading both biquads, which makes the circuit self-compensated. The cut-off frequency obtained is 230 Hz, which is suitable for ECG application. The ECG system requires a dynamic range of 44 dB when considering the amplitude variation of the ECG signal [17].

\[
DR_{\text{min}} = 20 \log \frac{ECG_{\text{max}}}{ECG_{\text{min}}/2} \tag{4}
\]

where ECG_{min} and ECG_{max} are the minimum and maximum ECG signal levels, respectively; i.e. 0.05 to 4 mV. For 44 dB DR (7.3 bits) ADC with a sinusoidal input signal of 50 mV, the minimum allowable input referred noise is 223.76 µVrms, which is calculated as:

\[
\text{Noise}_{\text{IRN(µVrms)}} = V_{\text{in}}/10^{(SNR)\text{dB}/20} \tag{5}
\]

The fourth order filter is shown in Fig. 11 and its design parameters are shown in Table 2. It provides a pass-band gain of 0 dB with a flat pass-band response. It provides a HD of 71 dB with input amplitude of 100 mV and frequency of 100 Hz. The achieved DR is 68.1 dB obtained with a THD of 40 dB at 220 mV signal and noise of 61.2 µVrms. The overall circuit consumes power of 7.2 nW with a supply voltage of 1.2 V. To verify the reliability and effectiveness of the proposed filter, simulations are performed for three different bias currents and supply voltages. Simulation results including frequency...
response, noise and THD are shown in Figures 12, 13 and 14 for different bias currents; i.e. 0.75 nA, 3 nA and 14 nA. Figure 15 shows the frequency response for different supply voltages; i.e. 1.1 V, 1.2 V and 1.3 V. The results obtained are tabulated in Table 3 and Table 4. The LPF is followed by an ADC. An ADC of 7.8 bits can be placed. To maintain the filter performance, a buffer is required to drive the successive stage. To fulfill the settling requirements, the bandwidth (BW) of buffer should be seven times greater than the signal BW [18].

Frequency response shown in Fig. 13 illustrates that the $-3$ dB bandwidth obtained by simulation at different current values of 0.75, 3 and 14 nA are 230, 329 and 1.4 K Hz with DC gain of 0, $-0.0$ and $-0.5$ dB, respectively. Input referred noise for the same setup is 8.1, 7.43 and 7.01 $\mu$V/$\sqrt{\text{Hz}}$, while the THD and DR are $-71$, $-82.11$ and $-88.30$ dB, and 68.1, 69.24 and 70.47 dB, respectively. The reliability and effectiveness of the circuit with different supply voltages are also observed, illustrating that the frequency response at 1.1, 1.2 and 1.3 V are 226, 230 and 238 Hz with DC gain of 0.01, 0 and $-0.063$ dB, respectively. Input referred noise is 8.1, 8.18 and 8.18 $\mu$V/$\sqrt{\text{Hz}}$ respectively. THD and DR are $-71$, $-71$ and $-71.2$ dB, and 68.1, 68.1 and 68.3 dB, respectively. The power consumption increases with increase in supply voltage. Figure 15 shows the frequency response at three different supply voltages, while the

Table 2  Design parameters of fourth order LPF.

| Parameters       | P-biquad | N-biquad |
|------------------|----------|----------|
| $V_{DD}$ (V)     | 1.2      |          |
| $Vb$ (V)         |          | 80 m     |
| $Ib$ (nA)        |          | 0.75     |
| Cut-off freq. (Hz) | 230     |          |
| $Q$              | 0.7      | 0.9      |
| $C1, C2$ (F)     | 4p, 10f  | 2.2p, 10f|

Fig. 12  Total Harmonic Distortion (a) 0.75 nA (b) 3 nA (c) 14 nA.
noise and THD graphs remain the same as in Fig. 10 and Fig. 8, respectively, because the values at different supply voltages are the same.

To verify the filter performance, an ECG signal is adopted from [19] and a 400 Hz signal is superimposed over the undistorted ECG signal and passed to the proposed LPF that attenuates the 400 Hz signal. Figure 16 shows the distorted ECG signal along with the filtered signal.

Table 3  Design parameters at VDD = 1.2 V.

| Bias current (nA) | 0.75 | 3 | 14 |
|------------------|------|---|----|
| Vb (mV)          | 80   | 120 | 180 |
| DC gain (dB)     | 0    | −0.06 | −0.5 |
| Cut-off freq. (Hz) | 230 | 329 | 1.4 K |
| Noise (V/√Hz)   | 8.1  | 7.43 | 7.01 |
| THD(dB)          | −71  | −82.11 | −88.30 |
| DR (dB)          | 68.1 | 69.24 | 70.47 |
| Power (nW)       | 7.2 | 28.9 | 130.8 |

Table 4  Design parameters at I_b = 0.75 nA.

| Supply (VDD) | 1.1 | 1.2 | 1.3 |
|--------------|-----|-----|-----|
| DC gain (dB) | 0.01 | 0 | −0.063 |
| Cut-off freq. (Hz) | 226 | 230 | 238 |
| Noise (V/√Hz) | 8.1  | 8.18 | 8.18 |
| THD(dB)      | −71  | −71 | −71.2 |
| DR (dB)      | 68.1 | 68.1 | 68.3 |
| Power (nW)   | 6.38 | 7.2 | 8.45 |

Fig. 16 ECG signal (a) with 400 Hz distortion (b) filtered waveform.

Layout of the proposed circuit occupies an area of 291.7750 µm × 490.355 µm; i.e. 0.143 mm². Figure 17 shows the layout of the circuit.
5. Discussion

Simulation results show that the filter designed in this study having 230 Hz frequency is suitable for portable ECG detection system. The DR of an ECG signal must be greater than 44 dB, and this circuit provides a very high DR of 68.1 dB. To validate the filter performance, an ECG signal with 400 Hz distortion is added and passed through the designed filter which attenuates the 400 Hz frequency and satisfies the filter performance. A very low power of 7.2 nW is used with a supply voltage requirement of 1.2 V, which is acceptable for portable devices, because for portable devices the power consumed should be very low for the circuit to operate for a prolonged period of time [20]. Supply voltage should also be low keeping in mind the size and weight of the circuit. Low frequency circuits are dominated by flicker noise, which is reduced in this design by keeping the length of the transistors slightly larger than the minimum acceptable value and by placing P-biquad at the first stage because it has lower flicker noise compared to N-biquad. To compare this filter with other state-of-the-art designs, a figure of merit (FOM) is adopted from [21] and given in equation (6) below:

\[
FOM = \frac{P}{Nxf \times DR}
\]  

where \( P \) is the power consumption of the filter, \( N \) is the order, \( f \) is the cut-off frequency and \( DR \) is the dynamic range. The lower the FOM, the better will be the performance. Thus the designed structure shows better performance in terms of FOM and THD. Comparison with other state-of-the-art designs are shown in Table 5.

6. Conclusion

This paper presents the designing of a fourth order LPF for portable ECG detection system. The proposed filter consists of one N-biquad and one P-biquad. Input and output common mode voltages are the same, which helps to cascade and design higher order filters. The filter is self-compensated, because although both biquads are attenuated by their bulk effects due to NMOS transistors in each biquad, they are in opposite direction. Both bulk affects are cancelled out, which neutralizes the gain to 0 dB. The circuit has a global feedback and a local feedback, which help to reduce the distortion and improve the linearity of the circuit. The HD3 obtained for 100 mVpp 100 Hz frequency signal is 71 dB and the inte-

![Fig. 17 Layout with an area of 0.143 mm².](image)

### Table 5 Comparison with other state-of-the-art filters.

| Parameters            | This Work [2019] | TCAS-I (2018) [14] | TCAS-II (2018) [17] | TCAS-I (2018) [9] | TCAS-II (2013) [18] | TBioCAS (2009) [7] |
|-----------------------|------------------|--------------------|--------------------|------------------|--------------------|--------------------|
| Technology (nm)       | 130              | 350                | 180                | 350              | 350                | 180                |
| Supply Voltage (V)    | 1.2              | 1.5                | 1                  | 0.9              | 3                  | 1                  |
| Order                 | 4th              | 4th                | 5th                | 4th              | 4th                | 5th                |
| Cut-off frequency (Hz)| 230              | 100                | 50                 | 100              | 100                | 250                |
| DC Gain (dB)          | 0                | -0.09              | -6                 | -0.05            | 0 (with compensation circuitry) | -10.5 |
| Noise (µVrms)         | 61.2             | 39.38              | 194                | 80.5             | 29                 | 340                |
| Power (nW)            | 7.2              | 5.25               | 350                | 4.26             | 15                 | 453                |
| THD(dB)               | -71              | -50                | < -50              | -50              | -60                | -49                |
| DR (dB)               | 68.1             | 56.9               | 49.9               | 48.2             | 55.7               | 50                 |
| FOM (fJ/dB)           | 115              | 230.66             | 28056.11           | 220              | 673.24             | 7248               |
grated noise is 61.2 µVrms, which provides a DR of 68.1 dB, while the 40 dB THD is obtained with an input signal of 220 mVp. Total power consumed by the circuit is 7.2 nW with a power supply of 1.2 V. To verify the reliability and effectiveness of the circuit, the proposed LPF is simulated at different bias current values and supply voltages. The proposed LPF provides the best performance in terms of FOM and THD.

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