Design of Amplifier for Wearable Human ECG Sensor with Low Power and Low Noise

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Abstract: Electrocardiograph (ECG) data is an important index to determine the human heart state, which helps diagnose heart disease in an early stage. Since the ECG signal is instantaneous, it is important to make the ECG signal collector wearable and have good battery life. The wearable ECG devices need to have certain properties like interference suppression ability of acquired signal, low power consumption, low noise, and high integration, putting forward crucial requirements for the design of the amplifier. To meet the properties, the front-end analog processing circuit with interface input buffer stage structure and post-amp structure was proposed here, which has the characteristics of small size, low power consumption, low input referred noise, fair common-mode rejection ratio, and high input impedance. Besides, as one of the industrial-grade circuit simulation software, LTspice was used to design the circuit structure and analyze the corresponding performance. According to the circuit design and simulation testing, it turned out that the circuit in this work can be quite simple, and all the performance indexes met the practical demands. The frequency range was 0.1Hz–100Hz, the voltage was 1.2V, the differential gain was 40.37dB, the total integrated input-referred noise was 3.48μVrms, and the total power consumption was 1.75μW. In summary, our data indicate that the ECG device we design is small enough to be wearable and has low power consumption.

1. Introduction

In the past several decades, the real-time heart monitor has played an important role in health care since the risk of people being diagnosed with heart diseases increases. The aging population trends to rise year by year, but more and more young people are getting a heart attack because of electronic devices obsession and unhealthy lifestyle. Heart disease kills hundreds of thousands of people in the world every year, and tens of millions of people suffer from cardiovascular disease [1]. It is necessary for the growing demand of the market to have an electrocardiogram (ECG) popularized. ECG devices make it possible for the patients to detect the disease in an early stage [2].
But the problem is that heart attack can be either sudden or unpredictable, which means it can only be prevented by real-time monitoring. Meanwhile, the analog front end (AFE) of ECG devices in the hospital are large in volume and high in power consumption [3]. To solve this problem, the design of the wearable AFE has been proposed. The wearable AFE can provide ECG devices with various properties, such as interference suppression ability of acquired signal, low power consumption, low noise, and high integration [4]. With the AFE, ECG devices can finally be wearable.

During the research of wearable ECG devices, researchers make multiple choices to realize the function. Xiaoyan Ling proposed a system that contains the Interface protection circuit, amplifying circuit, driven-right-leg circuit, filter circuit. This system acted well in noise suppression [5]. Farida Saeidian suggested a three-stage structure that also did a great job in noise suppression and its semiconductor chips on the smaller size [6]. ChunXiao Wei suggested using a low-noise preamplifier (LNA) to filter out the interference caused by electrode imbalance. According to her design, the high pass cutoff frequency was 0.52 Hz, the low pass cutoff frequency is108.6 Hz, and the equivalent analog input noise integral in the band is $3.5 \mu V_{\text{rms}}$ [7]. XiaoLei Zou proposed an ECG signal acquisition analog front-end circuit designed which used channel multiplexing technology to reduce the circuit power consumption and scale. It mainly consisted optical fiber amplifier (OFA), a multi-channel data selection circuit, an instrumentation amplifier, and a variable gain amplifier. The ECG signal acquisition analog front-end circuit and layout are designed in 0.18$\mu m$ CMOS technology. The simulation results show that the circuit consumed 140 $\mu A$ and gave 40–60 dB gain and 130 dB Common-mode Rejection Ratio (CMRR) in the bandwidth 7.6 kHz [8].

However, they mention little about power consumption, which is also the critical part of wearable ECG devices and has rarely been studied directly. Without proper power consumption, the battery's charge could bother consumers and influence its practical applicability. In addition, though they have turned out good noise suppression, it can be better.

This paper aims to develop an overarching framework to make the wearable ECG device with great noise suppression and low power consumption. In this case, a CMOS Resistive-Feedback ECG amplifier circuit is used and connected to a driven-right-leg circuit. This work's key contribution is its solution to achieve low power consumption, low noise, and high integration in wearable ECG devices.

2. Method

The Front-end Analog Processing Circuit designed by us was composed of Interface Input Buffer Stage Circuit, CMOS Resistive-Feedback ECG amplifier circuit, Filter Circuit, and Post-amp Circuit. The overall structural block diagram of the Front-end Analog Processing Circuit is shown in Figure 1. It first raised signal filtering function, then amplified the signal while limiting the peak to a certain range.

![Figure 1. Schematic of the circuit](image)

2.1. Operational Transconductance Amplifier (OTA)

As mentioned previously, given ECG signals' characteristics, the circuit of our design should take input
impedance, linearity, low noise, and other factors into consideration. And we should also try to weaken the impact of the industrial frequency interference and the baseline drift caused by breathing. The CMOS Resistive-Feedback ECG amplifier circuit has the characteristics of small size, low power consumption, low input referred noise, fair common-mode rejection ratio, and high input impedance. The circuit requires high accuracy and stability, which suit the characteristics of the CMOS Resistive-Feedback ECG amplifier circuit. Operational Transconductance Amplifier was used in this circuit to amplifier the ECG signal. The structure of OTA, the circuit that is a project used, is shown in Figure 2. The target amplify gain is 40dB. The following formula determines the amplify gain of the circuit.

\[ \text{Gain} = \frac{1}{\text{Resistance} \times \text{Capacitance}} \]

Where \( R \) and \( C \) represent the capacitance showed in Figure 1. We choose a 2.5p capacitor and a 400p capacitor for the circuit. The calculation gain is at about 44.08 dB. It was purposely chosen higher to counter the signal weaken from the circuit. The amplified gain of this circuit is controlled by the capacitors, which could demonstrate higher precision than using resistors.

2.2. Filter Circuit

Due to human respiration, a high-pass filter is needed to obtain the ideal waveform. According to the characteristics of the ECG signal, the appropriate cutoff frequency should select to be 0.1Hz. In Figure 3, the high pass section (the Circuit inside the red circle) of this circuit was shown. This high pass filter contains two main components a capacitor which also acts as the load of the amplifier circuit, and a resistor. This formula's high pass frequency is determined by this formula, which means the value of resistance and capacitance decides the frequency.

Since the target high pass frequency is 0.1 Hz and the capacitance of the capacitor has been determined by the amplifier circuit. A resistor that has a resistance of 0.6 Tohm was needed. A normal
resistor that has this resistance will be huge and inconvenient for a wearable device. Therefore, using a pseudo resistor to achieve this value can be a good choice for us. Figure 4 shows the structure of our pseudo resistor.

![Figure 4. Structure of pseudo resister](image)

Meanwhile, the ECG signal has characteristics that are usually weak, which means its magnitude is no more than mV. A large number of electromagnetic interference signals are often mixed in the Interface Input Buffer Stage Circuit. Because of that, a Low-pass Filter was required to remove part of the interference signal. Also, because the ECG signal belongs to a low-frequency signal whose energies are mainly below a few hundred Hertz, our high-frequency signal's cut-off frequency was decided to be 100Hz. The high pass filter is being integrated with our OTA. The low pass circuit is shown (the Circuit inside the red circle) in Figure 5.

![Figure 5. Low pass filter](image)

### 2.3. Body Simulation

Since the ECG signals are biomedical, the ECG signals are usually weak and are low-frequency signals. And interference of the ECG signals is quite large. The interference is both from the inside of the body and the outside of the body, including myoelectric interference, respiratory interference, industrial frequency interference, etc. At the same time, the interference signals overlap with the frequency band of the ECG signals.

To simulate the human body signal's characteristics, a body signal simulation circuit was built for
our experiment. The schematic of this circuit is shown in Figure 6. This circuit use resister to simulate the interference from the electrode on each end of the body. And it uses three 200-ohm resistors to simulate the resistance between each end of the body. The current generator generates a 0.1A 60Hz current to simulate the low-frequency noise of the body.

3. Result and Discussion

Table 1: Performance compare with previous work

|                         | ANSI-AAMI EC13 [9] | Chunxiao Wei, 2020 [10] | Tsung-Heng Tsai, 2012 [11] | Xiaohuo Zou, 2020[12] | Our Performance |
|-------------------------|--------------------|--------------------------|-----------------------------|-----------------------|-----------------|
| Frequency Range         | NA                 | 0.52Hz -108.6Hz          | NA                          | NA                    | 0.1Hz – 100Hz   |
| Voltage                 | NA                 | 1.8v                     | 1v                          | 1.8v                  | 1.2v            |
| Differential Gain       | 40dB               | 47.6dB-59.8dB            | 50dB                        | 40dB                  | 40.37 dB        |
| Total integrated input-referred noise | < 10 μVrms | 3.5 μVrms                  | NA                          | 86 nVrms              | 3.48 μVrms      |
| Total power consumption | NA                 | 70μW                     | 453nW                       | NA                    | 1.75μW          |

Table 1 is our experiment result compared to other previous work and industry standards. This circuit did a good job on total integrated input-referred noise, total power consumption, and common-mode rejection ratio. Our goal is to build a wearable ECG sensor, and this performance is crucial for a wearable device. To obtain these results. We prefer these three simulation tests with LTspice.

3.1. Result Analysis

The first test is AC sweep from 1mHz to 100kHz. This test will measure the mid-range gain and the bandwidth of our circuit. The graph that we show in figure 7 is the result of this test. This graph shows our bandwidth measurement. By measuring the graph, the mid-range gain is located at 40.37dB. Therefore, the bandwidth is limited by the frequency at three dB less than the mid-range dB, about 37.37dB. By measuring the graph, we have 100.26mHz at about 37.425dB and 99.608Hz at about 37.343dB. Therefore, the bandwidth of this circuit is between 0.1Hz to 100Hz.
This graph shows the output noise analysis result of our circuit. By measuring the graph, we can see that our total output-referred noise is about 363.41μV since this test has only resulted from the outputted-referred noise of the circuit. The calculation was needed to prefer to obtain the input-referred noise. Input-referred noise is calculated by dividing the Output-referred noise with mid-range gain.

![Noise analysis simulation](image)

Figure 8. Noise analysis simulation

This graph is the CMRR measurement of our circuit. Our common-mode rejection signal could be measured by duplicating our circuit and adding a common signal input to the new circuit. This is a very important specification that shows our circuit's ability to remove the common-mode signal when measuring the ECG signal. We can see our CMRR is at about 94.7dB at 30Hz. And the CMRR is constantly above 90dB before 100Hz. Since our circuit's measured bandwidth is 0.1Hz to 100Hz, we have an excellent CMRR across our entire bandwidth.
3.2. Discussion

The wearable ECG sensor is quite important for the user to detect their heart condition. This article designed the wearable ECG sensor circuit, which has a low power consumption feature.

The research method in this work is mainly based on the spice simulation. Since the target is to build a wearable device, power consumption is very important for this design. Most of the power of the circuit is consumed by the amplifier. Because of that, this design circuit must use as few amplifiers as possible. Therefore, a CMOS Resistive-Feedback ECG amplifier circuit was choosing to implement in this circuit. Because the amplifier of the circuit is an OTA, compare to an Opamp, it has a much higher impedance. An Opamp-based circuit requires multiple amplifiers to increase the input impedance, which consumes a lot of power. A CMOS Resistive-Feedback ECG amplifier circuit only needs one OTA, which consumes much less power.

After the circuit design and calculation were finished, it was simulated in the LTspice circuit simulation software. LTspice, a kind of industrial-grade circuit simulation software, was used in this work to design the circuit structure and to analyze the corresponding performance. The first job is to build the circuit in LTspice and then use the AC sweep function to sweep the circuit's gain between 1mHz to 100kHz. After that, the noise analysis between 1mHz to 100kHz needed to be run to determine our circuit's denoise ability. Then, this circuit was duplicated, and the new circuit was given common signal input. Lastly, the AC sweep was run again to measure the common-mode rejection ratio of our circuit. By running this test, the performance of our circuit can be proved.

Since our experimental condition restricts, our wearable ECG sensor design is only based on LTspice simulation. More works needed to be done in the future, just like testing our design in real condition. Also, more noise reduction designs can be added to the circuit. The input-referred noise of this circuit is about 3.45 $\mu$Vrms. It can be better. At the same time, we also hope to implement an ADC module in this circuit so that the ECG signal can be read to the computer. By using a computer algorithm, the noise can be reduced, and automatic analysis can be achieved. Meanwhile, we hope to add more functions to this circuit in the future, such as detecting signals in motion, which need to take motion artifacts into consideration. Also, it is necessary to add a Bluetooth block to transmit data to mobile devices, so the user could upload the ECG data to make remote ECG monitoring possible.
4. Conclusion
On this basis, to sum up, everything that has been stated so far, our design is pretty successful on power consumption and size. By using LTspice simulation, we tested the performance of our circuit and proved its portability. The overall performance fits the aim of this work which is to design a wearable ECG sensor. Our data indicate that this design has made a great improvement on circuit size and its power consumption compared to the previous work. These are the key factor for the exact purpose of a wearable ECG circuit. This design enables us to better implement ECG detection ability to the wearable items like watch or clothes, to help the patient with cardiovascular diseases. Future research should be devoted to the development to lower the circuit's noise and common rejection ratio. As also recommended above, future research should focus on the digital backend of the ECG signal collection like ADC or Bluetooth module. With the help of Computer Engineering, the ECG signal collected can be better analyzed to provide practical help for the patient. We hope this work can help the people suffering from cardiovascular diseases and lower the death rate of cardiovascular diseases.

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