Design And Implantation of An ECG Signal Amplifier and Filter Processing System

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Abstract. As advancements in semiconductor technology converge with the growing focus on cardiovascular diseases, there's a discernible push for Electrocardiogram (ECG) signal monitoring technologies that prioritize reduced power consumption and noise. This paper introduces a front-end architecture for the ECG signal monitoring system, comprising modules for acquisition, instrumentation amplification, and filtering. Given the varied noise profiles in ECG signals, our design harnesses a coupled front-end acquisition, a capacitive feedback instrumentation amplifier with a single op-amp, and uses a chopping technique. This approach primarily targets interference mitigation during acquisition and amplification, all while maintaining minimal power usage. Subsequently, an effective filter circuit tailored is added to remove noise modulated by the chopper. This design refines the ECG system's front-end, minimizing disturbances to subsequent circuits and enhancing the accuracy of the back-end ADC and digital processing part. This bioelectric monitoring system's design, characterized by low power consumption and minimal noise, is also well-suited for portable medical devices.

Keywords: ECG Signal, instrumentation amplifier, chopping, filtering, low noise.

1. Introduction

Cardiovascular disease stands as the leading cause of death worldwide, with a concerning trend of affecting younger populations. Diagnostic tools for these diseases are often prohibitive in cost, cumbersome, and unsuitable for extended monitoring. This underscores the growing significance of low-power, cost-effective wearable biomonitoring devices in the medical electronics realm. Concurrently, the focus on algorithms and circuitry for ECG signal processing is intensifying. The accuracy of these devices not only establishes the reliability of their data but also shapes the precision of doctors' cardiovascular diagnoses [1].

This paper presents a feasible low-power, low-noise, architecture for processing ECG signals. It consists of acquisition, amplification and filtering sections. Firstly, this paper delves into the characteristics of standard ECG signals. The emphasis is laid on the two predominant interferences encountered during ECG signal capture. An exploration into the origins, frequency traits, and initially describes the classical methods of removing them from the actual circuits. Secondly, through the characteristics of the interferences mentioned above, presenting the design of a system's front-end dedicated to ECG signal processing. The innovative approach prioritizes eliminating most disturbances during the acquisition and amplification phase, distinguished from the conventional multi-stage digital filtering. Subsequent standard filtering processes address residual noise. This methodology enhances the ECG processing system's overall accuracy while diminishing the circuit's power consumption and size in the filtering segment.

2. Theory of ECG Processing

2.1. ECG Basic

The Electrocardiogram (ECG) is an essential tool for evaluating the heart's rhythm and electrical dynamics. This signal generates from ion movements within and outside cardiomyocytes, termed depolarization (contraction) and repolarization (relaxation). A standard ECG trace comprises the P wave (attributed to atrial depolarization), QRS complex (a result of atrial repolarization and ventricular depolarization), T wave (due to ventricular repolarization) [2]. The activity of the heart is not only reflected in the heart rate, but more importantly, it is reflected by the characteristics and parameters of different bands in the ECG. Figure 1 shows a characteristic ECG trace. Defined as a low-frequency electrical signal, its bandwidth spans from 0.05 to 100Hz, with a significant portion below 35Hz. Typically, its amplitude varies between 0.01 to 4mV, with 1mV as a common value [3]. To obtain an ECG signal, specialized electrodes are placed at designated sites on the human body, a technique known as electrocardiographic lead. Presently, the conventional 12-lead system stands as the globally recognized standard for ECG lead systems [4]. A typical ECG signal is shown in figure 1.

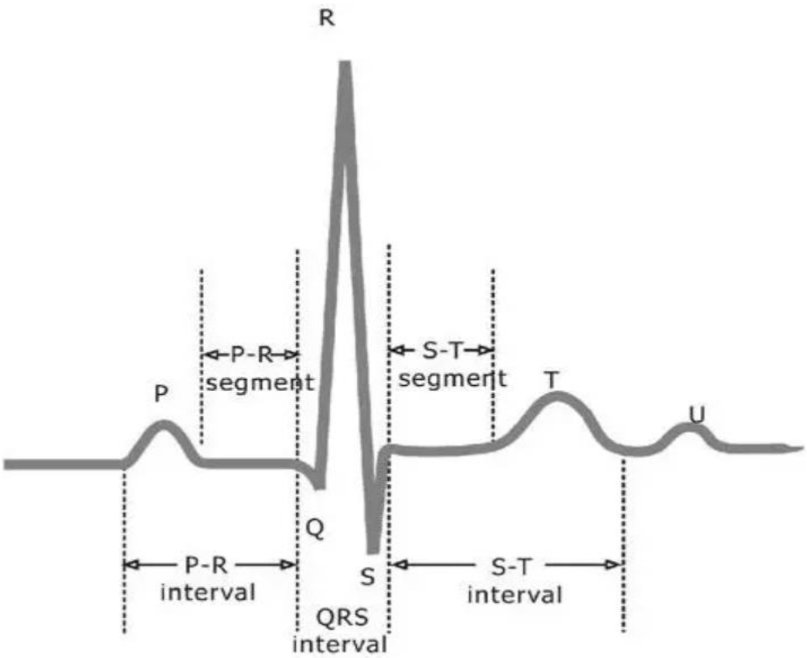

Figure 1. A typical ECG signal [3]

2.2. Interference Analysis

2.2.1. Noise in biopotential sensing

The bioelectrical signal in the human body has the characteristics of low magnitude and low frequency. Therefore, the acquisition process of the original bioelectrical signal is greatly affected by noise. There are usually two types of noise in a circuit, Thermal noise (white noise) is caused by the collision of carriers with the atomic lattice in the MOS transistor. Flicker noise (1/f noise) rises from traps linked to contamination and crystal defects in MOS transistors. The capture and release of carriers by these traps, governed by specific time constants, produce a noise signal primarily concentrated at lower frequencies. Considering the characteristics of bioelectrical signals, we can assume that 1/f noise is particularly detrimental for biopotential sensing because it works in low frequency bands. The feature of circuit noises is shown in Figure 2.

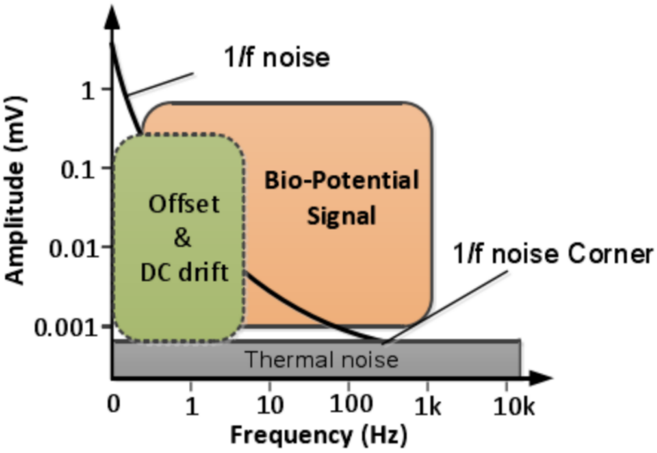

Figure 2. Feature of Circuit Noise [4]

2.2.2. Types of artifact in ECG signal

The ECG signal has the characteristics of strong noise background interference, and it is very easy to receive interference from external interference sources. Hence, the goal of the ECG signal acquisition and processing system is to capture a signal devoid of noise. The types of artifact sources of ECG are:

1. Power-line interference. Electromagnetic fields caused by a power-line or electromagnetic interference received using the human body as an antenna represent a common noise in the ECG, this type of noise occurs when measuring any type of surface signal. It usually manifests as a sinusoidal interference at 50/60Hz, possibly accompanied by several harmonics. Power-line interference entirely overlays the low-frequency part of ECG waves found in the P wave and T wave.

2. EMG interference. Noise generated by muscle movement is also a major interference factor in the measurement of ECG signals. This type of interference significantly overlaps with the PQRST complex and is characterized by its high frequency.

3. Motion Artifacts. Motion artifacts are mainly caused by changes in electrical resistance caused by the stretching of the surrounding skin measured by the electrode. This type of interference is similar to the interference caused by baseline wander, acts on each segment of the PQRST at the same time, and appears as a low-frequency noise, but its larger magnitude can also cause confusion in the QRS segment. Motion artifacts are often the main cause of mismeasurement of ECG signals.

4. Baseline wandering. Baseline wander is attributed to electrode-skin impedance mismatches, as well as the subject's movements and breathing. This interference usually manifests as a "drift" of the ECG signal along the overall X-axis, this results in the entire signal deviating from its typical baseline. As a low frequency interference, baseline drift interference is often eliminated by digital filtering at the back end [5].

5. High-frequency noises in the ECG (Such as electromagnetic interference in the air.

The following table 1 shows the interference in ECG signal processing.

Table 1. Types of artifacts of ECG Signal

Causes	Circuit Noise		Artifact during measurement				
Interference Types	Thermal Noise	Flicker (1/f) Noise	Power-line Interference	EMG interference	Motion Artifacts	Baseline wandering	Other HF Noise
Frequency characteristic	Constant	Low Frequency	50/60Hz usually,	High Frequency	Low Frequency	Low Frequency	High Frequency
Typical value				Up to 30Hz	1~10Hz	Often 0.05~0.5Hz	

In ECG signal processing, the commonly used filter circuit primarily consists of a HPF, LPF, and a 50Hz notch filter. But in the following, a design will try to deal with interference signals from the very front.

3. Structure of ECG Signal Process System

3.1. Signal detecting and amplifying circuit design

After acquiring the original ECG signal through multistage amplification, most of its mixed noise comes from the first stage, so the first stage amplification needs a large gain. When the signal is collected from the biological electrode, the resistance value of the electrode and the resistance value of the amplifier are divided, the attenuation of the signal will be larger, and the interference of noise will be more serious, so the input impedance of the amplifier must be large enough. In order to suppress power frequency interference from 50/60Hz, the amplifier must also have a sufficiently large common-mode rejection ratio to suppress common-mode interference. Building on the prior analysis and considering the characteristics of the ECG signal, we need a front-end circuit with a higher input impedance, a higher CMRR, a lower noise impact, and a lower power consumption. Figure 3 is a Capacitance-coupled chopper instrumental amplifier (CCIA) with OTA-based.

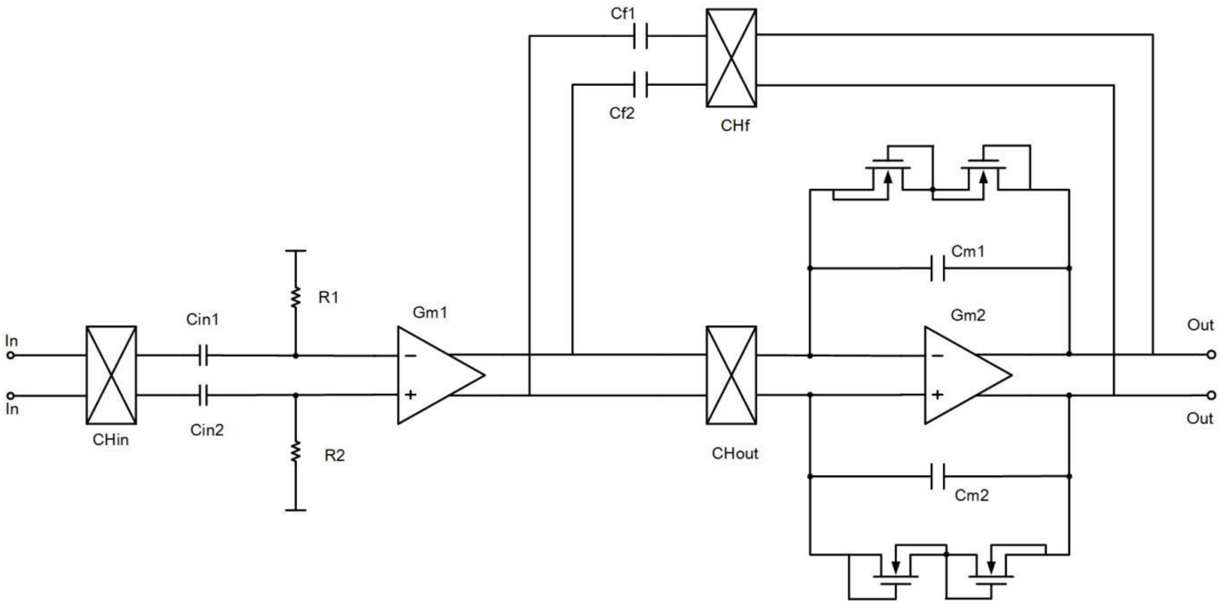

Figure 3. CCIA ECG amplifier (Photo/Picture credit: Original)

Two input capacitor Cin1 and Cin2 and two bias resistors form the AC-coupled front-end, each pair of RC forms a HPF which eliminate electrode offset potentials. At the same time, it plays a protective role in the event of failure in the amplifier input stage. Figure 4 is the AC-coupled front-end.

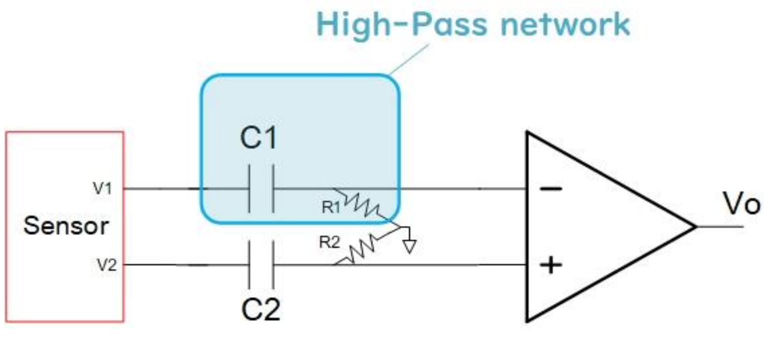

Figure 4. AC-coupled front-end [6]

The amplifying part adopts the structure of a capacitance-coupled instrument amplifier, and contains a single-stage OTA amplifier, feedback capacitor Cf, feedback resistor Rf. For a single CCIA structure, this structure adopts capacitive coupling, which can isolate direct flow, and only uses one op amp, which has low noise and low power consumption [6, 7]. The transfer function is:

$$H(s) = -\frac{R_f C_{in} s}{1 + R_f C_f s} \quad (1)$$

According to Formula 3. 9, its high-pass cutoff frequency is jointly determined by Rf and Cf. In order to reduce its cutoff frequency, we need a large Rf. In bioelectricity devices, we often need to avoid the use of large resistors, so we use a Mos pseudo resistor structure as the resistance [8]. The circuit is shown in Figure 5.

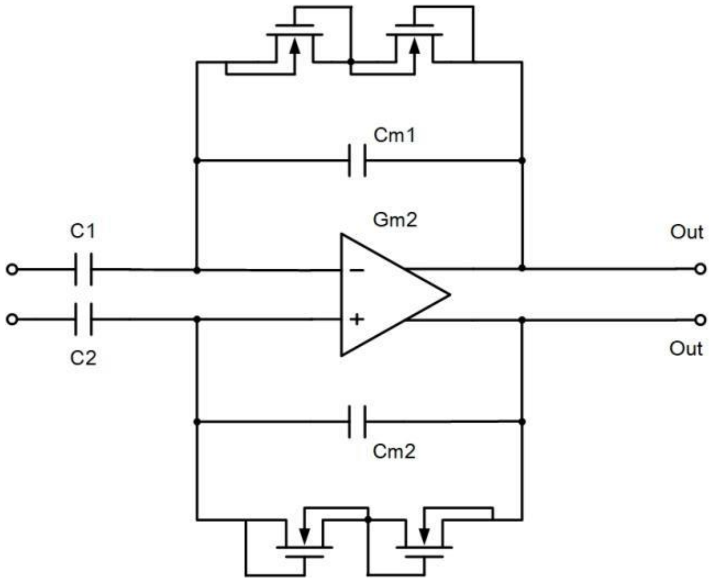

Figure 5. Capacitance-coupled IA [8]

In this case, the gain and cutoff frequency of the structure are defined by the following formula [9].

$$A_M = C1/C2 \quad (2)$$

$$f_L = 1/(2\pi \cdot R_f \cdot C_2) \quad (3)$$

$$f_H = Gm/(2\pi \cdot A_M \cdot C_L) \quad (4)$$

For mitigate 1/f noise, voltage offsets and drifts. This paper use chopper stabilization technique in this amplifier. Figure 6 illustrates the flow of a chopping technique for denoising.

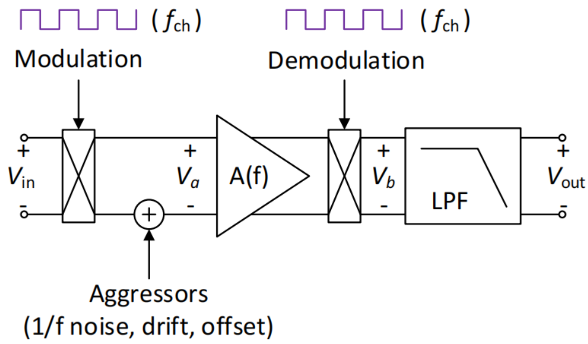

Figure 6. Chopper stabilization technique [9]

The acquired signal passing through chopper one will be modulated to the odd harmonic frequency of the chopper frequency. After input Gm1 through the AC-coupling front-end, the original signal will be contaminated with the flicker noise (1/f noise) and offset in the circuit, and after amplification, it will be demodulated by chopper 2. At this time, the signal will drop back to the low frequency while the flicker noise and offset are modulated to the chopper frequency, and the two are separated in the frequency domain [10]. The two signals pass through the second amplifier and are output to the back-end filter section. The addition of feedback loop can further improve the magnification of the structure.

In order to obtain sufficient gain while suppressing 50/60Hz common-mode noise from power frequency interference, we use single-stage OTA amplifiers for the amplifier part, OTA amplifier structure has good common mode rejection characteristics. Figure 7 shows the transistor level circuit of the amplifier.

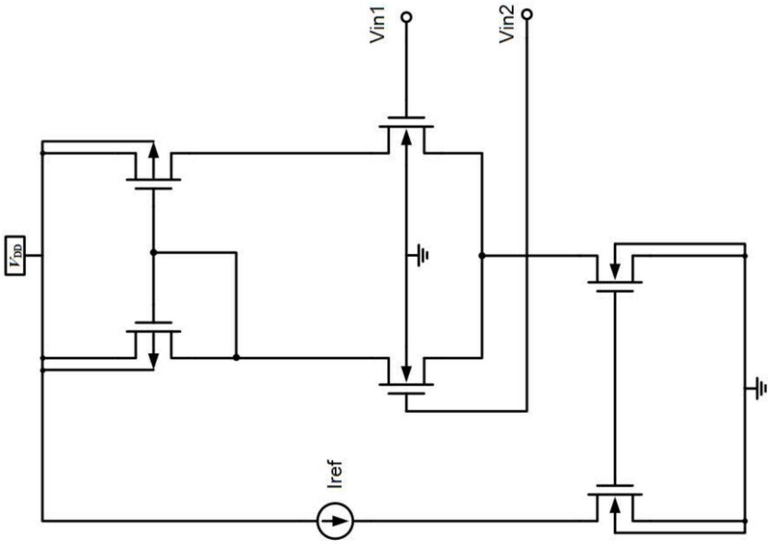

Figure 7. OTA op-amp (Photo/Picture credit: Original)

3.2. ECG signal filtering circuit design

The ECG signal operates within a frequency range of 0.05 Hz to 100 Hz. For the filtering process, we've designed a circuit comprising a HPF, a LPF, and a right-leg driver circuit [11]. Figure. 8 is a filter circuit of ECG Signal Processing system. The cutoff frequency for the low-pass section can be set by adjusting the values of C1 and R3, while the cutoff frequency for the high-pass section can be tuned by modifying the values of C2 and R2. After traversing the right-leg drive amplifier (RLD amp), the residual common-mode noise is fed back into the human body via the right-leg electrodes. This strategy significantly mitigates the impact of common-mode interference, thereby enhancing the system's overall common-mode rejection ratio [12]. Figure 8 shows the filter circuit.

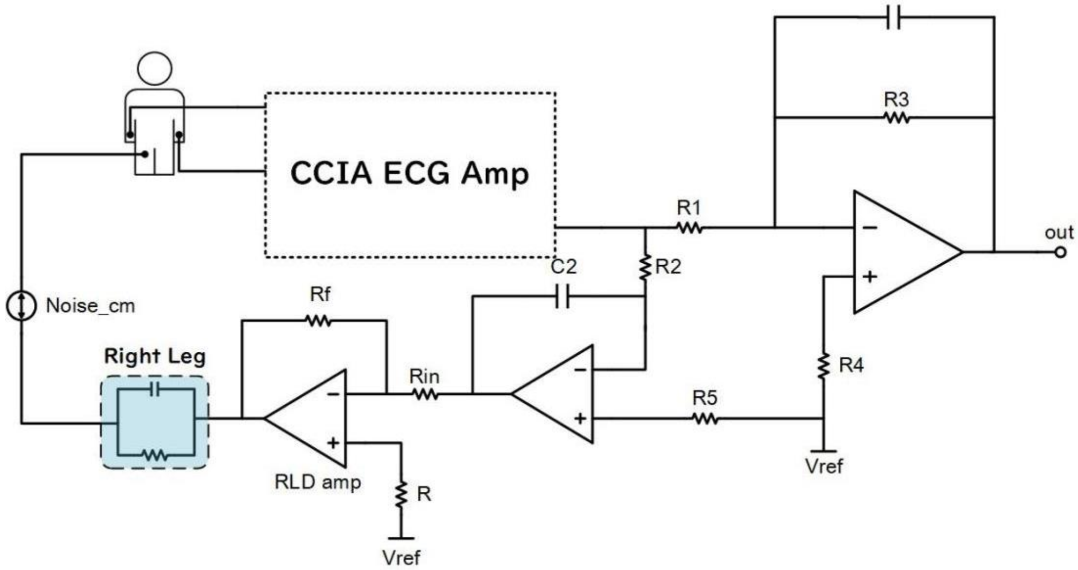

Figure 8. Filter circuit (Photo/Picture credit: Original)

Through the suppression of 50/60Hz power frequency interference by OTA amplifier, the isolation of the input side, and the separation of 1/f noise by chopping technology, we successfully removed most of the noise.

4. Conclusion

This paper introduces an architecture of the front-end section of an ECG signal processing system, encompassing acquisition, amplification, and filtering modules. This front-end's AC-coupled design functions akin to an HPF. By tweaking the RC on both sides, the bandwidth of this filter is adjustable to mitigate the low-frequency noise highlighted in Chapter II. The amplification segment utilizes a two-stage instrumentation amplifier with a capacitive coupling, ensuring reduced power consumption compared to dual-op-amp and tri-op-amp variants. A MOS pseudo-resistor structure replaces the need for large resistors throughout the circuit. By incorporating chopper technology, the signal's low-frequency noise is differentiated from the bias interference created by the op-amp in the frequency domain. The subsequent filtering link ensures that the chopper frequency noise is filtered, while the overall suppression of signal which frequency away from the standard ECG frequency noise as well as interference, and adds a right-leg drive circuit to further suppress the 50/60Hz industrial frequency interference. This design efficiently curtails major ECG signal noise at the front end. The filter's performance can be fine-tuned by adjusting specific electronic component parameters in each segment, facilitating easy circuit optimization for diverse environments.

The front-end circuits presented in this paper effectively mitigate or remove noise from external environmental sources, internal bodily disturbances, and inherent circuit mismatches. While the integration of chopper technology enhances system accuracy, it simultaneously poses challenges. Notably, chopper modulation can lead to issues like DC mismatches that are tough to manage, and the chopper itself may introduce additional disturbances. In this design, since demodulate prior to the second-stage amplification, noise generated by this stage remains. Thus, it might necessitate increasing the first stage's gain to achieve an optimal signal-to-noise ratio. This suggests that a more efficient structure might be available for standalone op-amps.

References

[1] Jin J. Screening for cardiovascular disease risk with ECG. Jama, 2018, 319 (22): 2346 - 2346.

[2] Ahmed W, Khalid S. ECG signal processing for recognition of cardiovascular diseases: A survey. 2016 Sixth International Conference on Innovative Computing Technology (INTECH). IEEE, 2016: 677 - 682.

[3] Houssein E H, Kilany M, Hassanien A E. ECG signals classification: a review. International Journal of Intelligent Engineering Informatics, 2017, 5 (4): 376 - 396.

[4] Bharadwaj A, Kamath U. Accurate ecg signal processing. Techniques for accurate ECG signal processing, Published in EE Times Design (http://www. eetimes. com/design), 2011.

[5] Kher R. Signal processing techniques for removing noise from ECG signals. J. Biomed. Eng. Res, 2019, 3 (101): 1 - 9.

[6] Yuliang Ma. Research and Design of Low Noise Instrumentation Amplifier. Soochow University, 2022.

[7] Bagheri A, Salam M T, Velazquez J L P, et al. Low-frequency noise and offset rejection in DC-coupled neural amplifiers: A review and digitally-assisted design tutorial. IEEE transactions on biomedical circuits and systems, 2016, 11 (1): 161 - 176.

[8] Guglielmi E, Toso F, Zanetto F, et al. High-value tunable pseudo-resistors design. IEEE Journal of Solid-State Circuits, 2020, 55 (8): 2094 - 2105.

[9] Tu C C, Lin T H. Measurement and parameter characterization of pseudo-resistor based CCIA for biomedical applications. 2014 IEEE International Symposium on Bioelectronics and Bioinformatics (IEEE ISBB 2014). IEEE, 2014: 1 - 4.

[10] Chen Y P, Blaauw D, Sylvester D. A 266nW multi-chopper amplifier with 1.38 noise efficiency factor for neural signal recording. 2014 Symposium on VLSI Circuits Digest of Technical Papers. IEEE, 2014: 1 - 2.

[11] Yelei Wang. Development of high-performance ECG signal measurement and application system. AnHui Medical University, 2021.

[12] Guermandi M, Scarselli E F, Guerrieri R. A driving right leg circuit (DgRL) for improved common mode rejection in bio-potential acquisition systems. IEEE transactions on biomedical circuits and systems, 2015, 10 (2): 507 - 517.