# Application and research of two-stage amplifier in ECG signal

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**Abstract.** With the development of modern science and technology, electrocardiograph (ECG) technology has gradually become one of the most important detection tools in modern medicine. This article introduces the characteristics of ECG including weak signal, strong noise, low frequency range and strong signal randomness, and it mainly includes P waves, QRS wave group and T wave. Also, the processing flow of ECG is introduced, and eliminate the effects of baseline drift, power-line interference, and electromyographic interference by denoising. Also introduces the characteristics of two-stage amplifier and the importance of frequency compensation. Then the electro cardio signal is simplified to classical differential signal, and a two-stage amplifier circuit is designed to amplify it. The simulation result is 80.31dB DC voltage gain, 3kHz -3dB bandwidth and 72 degrees phase margin. So, it can provide sufficient stability and allow the system to remain stable in the face of parameter changes, external disturbances, or any uncertainties. This study can better use of two-stage amplifier to obtain complete and accurate ECG.

**Keywords:** electrocardiograph, denoising, frequency compensation, two-stage amplifier.

## 1. Introduction

The history of ECG technology can be traced back to the early 19th century, with the continuous development of times and technology, ECG technology has developed from the original handwritten record to digital record, becoming one of the most important electrophysiological detection tools in the modern medical field, and has had a positive impact on medical care, disease diagnosis and heart health monitoring [1]. Therefore, it has better helped patients with early medical diagnosis and saved countless lives. In this paper, the whole process of ECG signal processing and amplifier circuit are deeply investigated.

Firstly, this paper introduces the characteristics and processing flow of ECG signal. ECG signal is used to reflect the activity of the heart electrical signal, mainly composed of P wave, QRS wave group, T wave. ECG signal has the characteristics of weak signal, strong noise, low frequency range and strong randomness [1]. The processing flow of ECG signal mainly includes signal acquisition, denoising, filtering and amplification. The main purpose of denoising and filtering is to eliminate baseline drift, power-line interference and electromyographic interference, so as to obtain a complete ECG signal. Secondly, this paper introduces the characteristics of high gain, wide bandwidth, noise, design cost, energy consumption and so on. And the function of compensation circuit and its application in two-stage operation amplifier circuit are also discussed. In the simulation part, the filtered and de-noised ECG signals are simplified to a classical differential signal and use the two-stage amplifier circuit to amplify the signal. Through the introduction of this paper, readers can understand the characteristics and processing flow of ECG signal more deeply and can skillfully use the two-stage operational amplifier circuit.

## 2. ECG signal processing flow

### 2.1. ECG characteristic

#### 2.1.1. Normal ECG waveform

ECG is short for electrocardiogram. Electrocardiogram is a method to detecting and recording the activity of the heart, and it reflect the electrical signals of the different stages of the heart. Its waveform shape diagram is shown in Figure 1 below.

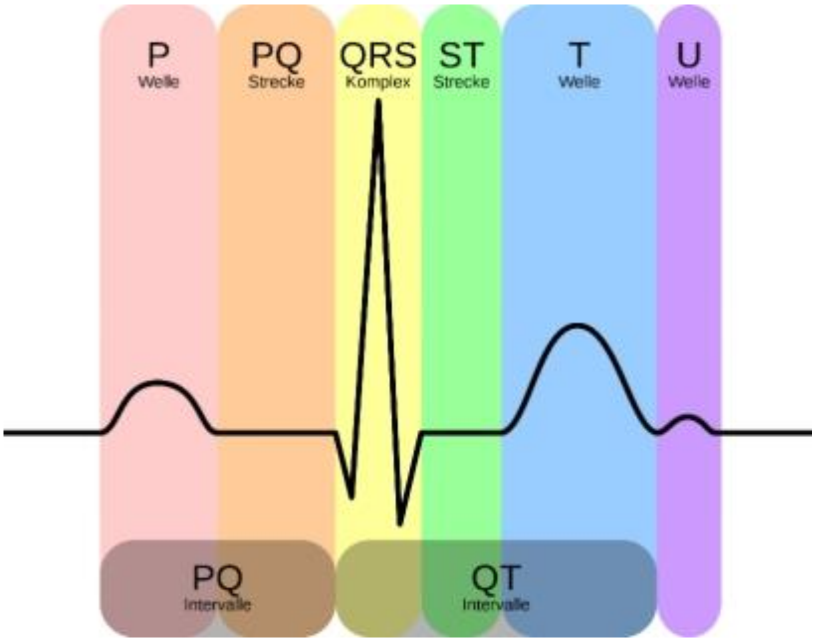


**Figure 1.** Simple ECG legend [2]

The figure above is a normal ECG signal waveform diagram, from which it can be seen that the ECG signal waveform is mainly composed of P wave, QRS wave group, and T wave.

P wave reflects the potential change of the left and right atria during the depolarization process. When the excitement generated by the atrial node propagates to the right and left atria, the potential difference between the excited and unexcited parts forms P wave [2]. So, the P wave represents the excitement of the atrium, the front half represents the excitement of the right atrium, and the back half represents the excitement of the left atrium [3].

The P wave is followed by the most important QRS wave group in the ECG, which reflects the process of depolarization of the left and right ventricles. R-wave is the main wave, so R-wave recognition is often the first step of ECG feature extraction. When the heart is diseased, the QRS wave group will widen and deform.

All depolarization has been completed in the ST segment, but repolarization has not yet begun. Normally it should be flush with the baseline, but when the heart appears necrosis and ischemia, the ST segment will have a significant deviation from the baseline.

The T wave of the electrocardiogram is a characteristic wave on the electrocardiogram, representing the repolarization process of the heart. In a normal electrocardiogram, the T-wave is usually an upward wave, indicating the changes in the electrical signals of the heart's ventricular muscles during repolarization [4].

### 2.1.2. Characteristics of ECG signals

ECG signals are unstable natural signals emitted by complex living organisms [5]. They have the following characteristics:

(1) The signal is weak, and the noise is strong, the ECG signal is a weak signal in the background of strong noise, its amplitude is 0.5 to 5 mV, and it is susceptible to a lot of noise interference.

(2) The frequency range is low, the frequency of conventional ECG signals is between 0.05 and 100Hz, while about 90% of ECG signals have an energy of 0.25 to 35Hz [6].

(3) The randomness is strong, and the law can be seen from a large number of measurements by statistical methods, and the signal cannot be described by a definite function, and easy to be affected by external signals [7]. Due to the difference of the human body, it increases its randomness.

(4) ECG signals are typical quasi-periodic signals, and there are great similarities between each periodic signal [8].

### 2.2. ECG process flow

The processing flow of ECG signal is mainly divided into input, filtering, denoising, amplification, and output. The following will mainly introduce filtering, denoising and amplification.

#### 2.2.1. Input

To obtain ECG signals, a wet electrode is first placed on the skin of the person to be measured, then the ECG signal is obtained through the wire, and finally it is presented on the screen through computer processing. But during the process of obtaining ECG signals, various types of noise can interfere with signal extraction. These include breathing noise, which results from chest and abdominal movements and manifests as low-frequency fluctuations in the ECG signal. Power interference, originating from AC power supply interference at 60 Hz or 50 Hz, can distort the signal with linear spectral components. Movement noise, caused by muscle movement or patient activity, leads to poor electrode-skin contact and appears as high-frequency noise in the signal. Additionally, environmental interference such as electromagnetic interference from power supplies, fluorescent lamps, and electronic equipment, as well as high-frequency radiation, can also impact the accuracy of the ECG signal.

#### 2.2.2. Denoising

The amplitude of ECG signal is millivolt level, which is easily affected by human breathing, muscle jitter and circuit equipment in the acquisition process, resulting in baseline drift, power-line interference, and electromyographic interference, which will cause damage to the characteristic parameters of ECG signal, make cardiac diagnosis cannot be carried out normally, and even cause serious medical accidents.

(1) Frequency domain analysis of ECG signals with baseline drift. Baseline drift is a weak low-frequency interference caused by slight muscle flutter induced by breathing during ECG signal collection [9]. The presence of baseline drift will affect the slope of ST segment in ECG. The noise frequency of baseline drift usually ranges from 0.05 to 2Hz. The amplitude of the ECG signal with baseline drift is higher when the frequency component is lower than 2Hz. The baseline drift spectrum in ECG is shown in figure 2.

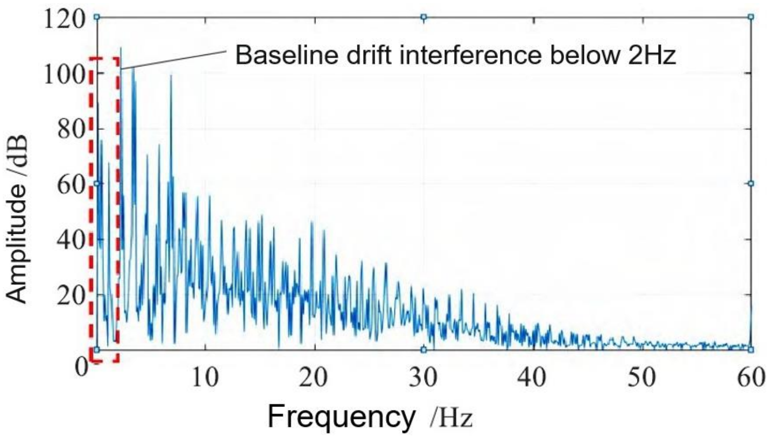


**Figure 2.** Baseline drift spectrum in ECG [10]

To eliminate baseline drift, a high-pass filter or band-pass filter can be used to filter out low-frequency drift. For example, a simple high-pass filter can be added to the circuit to separate the DC path and baseline drift. And f=1/(2piRC) can be used to calculate the transition frequency, so as to determine the filtering range.

The signal amplifier can also be used to properly amplify the signal and reduce interference. Reference electrodes can be used in the measurement to help stabilize the baseline. The reference electrode should be placed in a resting muscle area away from the measurement area. Avoid movement and muscle activity, which may cause baseline drift, and try to avoid or minimize these disturbances.

(2) Frequency domain analysis of ECG signals with power-line interference. Power-line interference is mainly caused by the electromagnetic reaction of the circuit caused by the instability of the AC current in the acquisition equipment in the process of ECG acquisition [11]. Power-line interference is characterized by a fixed frequency of 50Hz or 60Hz, and its noise component is mainly sine wave. In the spectrum, there is a high amplitude peak at 50Hz or 60Hz, and the power-line interference will affect the overall characteristics of the ECG signal. The power-line interference spectrum in ECG is shown in figure 3.

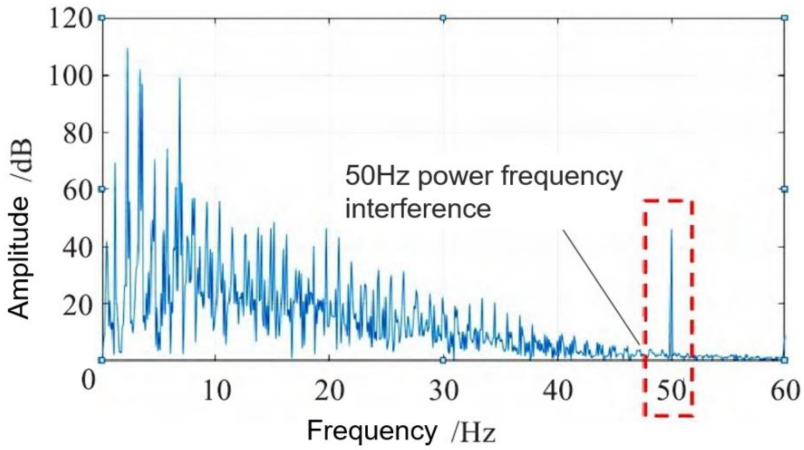


**Figure 3.** Power-line interference spectrum in ECG [10]

To effectively reduce the impact of power-line interference on equipment and improve signal quality, the shielded cables and filters can be used. For example, a 50 Hz narrow-band filter can be added to the circuit to eliminate the effect of power-line elimination.

And also, increase equipment grounding, use interference suppression equipment, use shielding materials, and regularly check and maintain equipment.

(3) Frequency domain analysis of ECG signals with electromyographic interference. Electromyographic interference is the high-frequency interference caused by muscle stimulation of the patch electrode during the acquisition of ECG signals [12]. The amplitude is generally not more than 1mV, but its frequency range varies widely, between 5Hz and 2000Hz, and it is superimposed with normal signals in the ECG signal spectrum. Usually, according to the characteristics of small energy distribution of ECG signal after 45Hz, it is used as the basis for judging the interference intensity of EMG signal. The electromyographic interference spectrum in ECG is shown in figure 4.

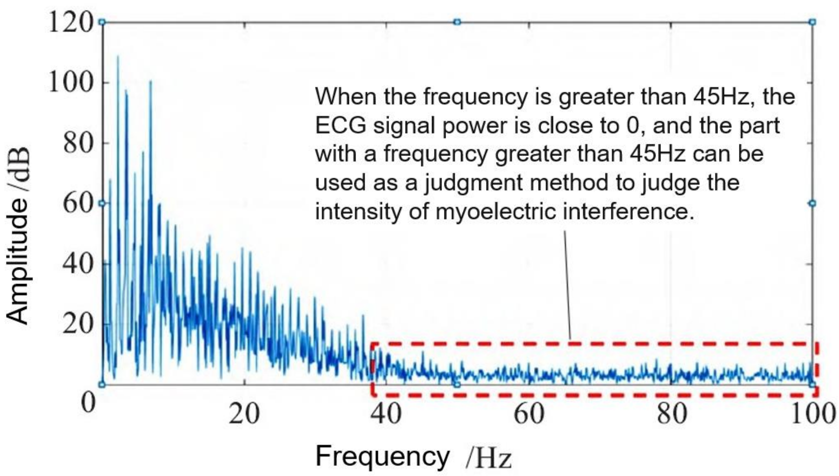


**Figure 4.** Electromyographic interference spectrum in ECG [10]

To eliminate the EMG interference, the electrode can be placed away from the muscle activity, use high quality electrodes and short connection lines, use filters to filter out the EMG interference, such as the use of differential amplifiers to offset the interference, and increase the signal sampling frequency.

### 2.2.3. Amplification

ECG signal amplification is to increase the amplitude of the signal so that it is easier to detect and measure the electrical activity of the heart. The voltage of the ECG signal is usually between a few microvolts and a few millivolts, and the lower voltage signal can be overwhelmed by noise, interference, or other environmental factors, making it difficult to accurately analyze. By amplifying the ECG signal, the amplitude of the signal can be significantly increased, making it easier to detect and analyze. In addition, amplifying the ECG signal also helps to enhance the signal-to-noise ratio and reduce the interference of system noise to the signal. Therefore, the amplification of the ECG signal helps to improve the accuracy and visualization of the signal, so as to better understand and analyze the ECG activity.

In the whole ECG signal processing process is the most critical amplifier circuit, the amplification effect will directly affect the signal output results. In this paper, the simulation and verification analysis of the two-stage operational amplifier are carried out to explore the actual influencing factors and effects.

## 3. Two-stage CMOS amplifier

### 3.1. Characteristic

As the most basic amplifier circuit in ECG signal processing, the two-stage amplifier has some prominent characteristics.

Firstly, it exhibits high gain, enabling it to amplify ECG signals to a larger magnitude, thereby meeting to signal processing and amplification requirements. And ECG signals are generally weak bioelectrical signals that can be amplified to a range suitable for analysis through the gain action of a two-stage amplifier. Secondly, it has a wide bandwidth, facilitating the transmission of high-frequency signals, hence excelling in high-frequency signal processing and communication systems. The electrical activity of the heart in the ECG signal is very rapid changes, and the wider bandwidth can maintain the accuracy of the signal and can better process and transmit the high-frequency part of the signal. Moreover, it has low distortion characteristics to ensure minimal non-linear distortion between the output and input ECG signals, meeting the stringent demands of high-precision amplification and signal reconstruction. Furthermore, its high input and output impedance provide favorable signal matching and interface properties, thereby minimizing reflections and losses between ECG signal sources and loads.

But the two-stage amplifier also has some disadvantages. Firstly, an increase in noise is an obvious disadvantage. Each amplification stage introduces a certain amount of noise, and consequently, the two-stage amplifier accumulates noise progressively. Secondly, there is a subsequent rise in the overall cost and complexity of the system. Finally, it will increase energy consumption.

There are also many applications for two-stage amplifiers, such as audio amplifiers, sensor signal amplification, and communication systems. It is capable of amplifying low-level audio signals to drive speakers, amplifying sensor signals to enhance measurement accuracy, and performing signal conditioning and processing to ensure reliable signal transmission and communication quality.

### 3.2. Frequency compensation

When employing a transistor as an amplifier, the inclusion of a Miller capacitor between the input and output can have a significant impact on the circuit's amplifier performance. To mitigate any adverse effects, a compensating capacitor and resistor can be utilized to modulate the bandwidth of the amplifier. This compensation network serves to stabilize the amplifier's gain characteristics and reduce undesired frequency response variations caused by the Miller capacitance. By appropriately selecting the values of the compensation capacitor and resistor, the overall bandwidth of the amplifier can be precisely adjusted, ensuring improved amplifier performance, and maintaining desired signal fidelity throughout the frequency spectrum.

### 3.3. Design of two-stage CMOS amplifier

First, the filtered and denoised ECG signals are simplified to classical differential signals and carried out simulation tests. Then the Cool Spice software is used to simulate it. It is a software tool for power integrated circuit design and simulation, and combines traditional SPICE emulators with silicon-based, transistor-level models. Therefore, I choose this software to simulate this two-stage amplifier circuit.

#### 3.3.1. Circuit design and methods

This two-stage amplifier is composed of a differential amplifier of the first stage and a common source amplifier of the second stage, which is shown in figure 5. It uses C018 PMOS and C018 NMOS transistors. And there are also designed a compensation circuit, which is composed of a resistor and a compensation capacitor.

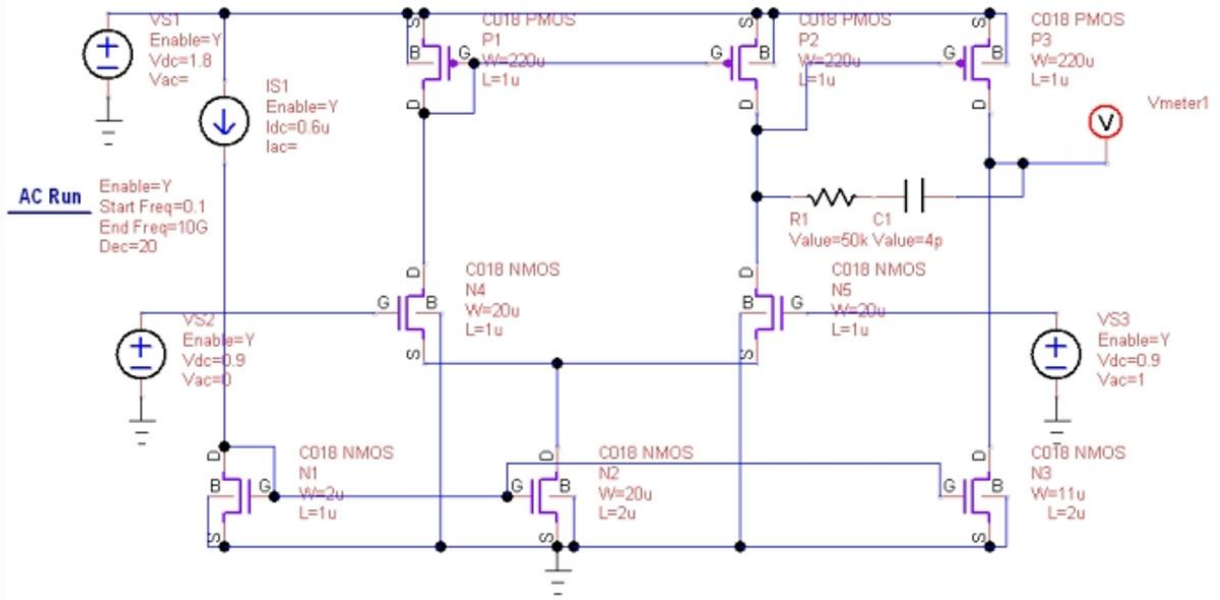


**Figure 5.** Designed circuit (Photo/Picture credit: Original)

#### 3.3.2. Simulation results

The simulation result is shown in figure 6.

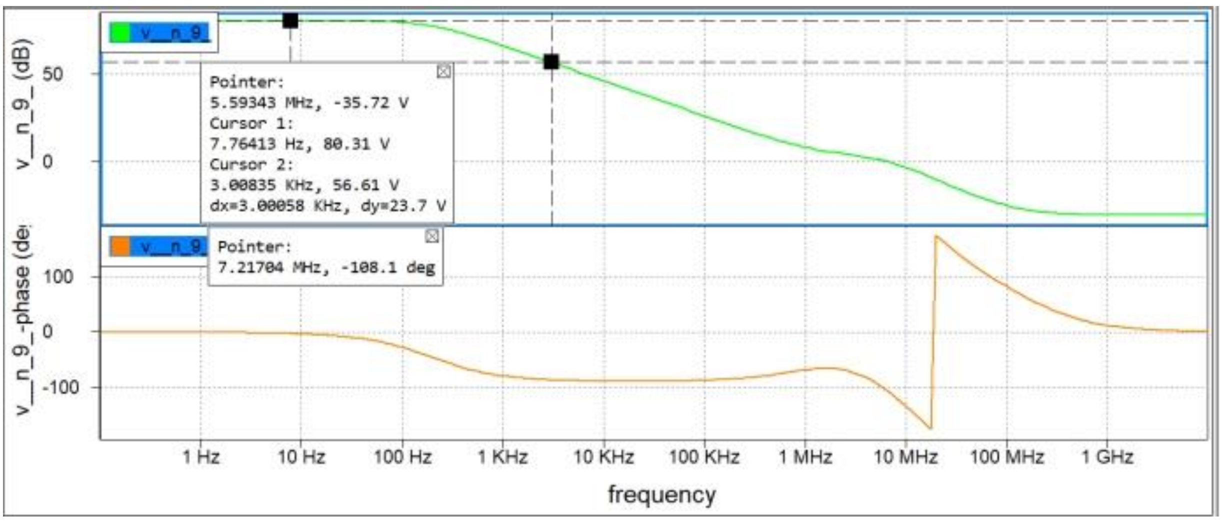


**Figure 6.** Simulation result (Photo/Picture credit: Original)

As it can be seen, the DC voltage gain is 80.31 dB, which is larger than 80 dB. The -3 dB bandwidth is approximately 3.008 kHz. The phase margin is about 72 degrees, which is larger than 40 degrees. So, it can provide sufficient stability and allow the system to remain stable in the face of parameter changes, external disturbances, or any uncertainties.

## 4. Conclusion

The simulation results obtained by simulation experiments are ideal. The gain of the two-stage operation amplifier circuit is 80.31dB, which makes the ECG signal obtain better amplification effect, and is more conducive to obtaining accurate information from the ECG signal. And the -3dB bandwidth is about 3dB, indicating that the system can effectively transmit signals in the frequency range of 3dB. The bandwidth can better ensure the signal quality and maintain a good signal transmission capability. And it has an ideal gain of 72 degrees, which shows that the circuit has good system stability and strong anti-interference ability.

However, in practice, if the input/output signal of the two-stage amplifier circuit exceeds the power supply range, the result may be distorted or saturated. In addition, the stability of the power supply voltage will also affect the performance of the two-stage operation amplifier circuit. Therefore, it is necessary to choose the appropriate power supply type and voltage regulation measures. And the two-stage amplifier has a certain bandwidth, that is, its frequency response range. In the high frequency range, the gain may decrease, and the phase response may cause waveform distortion. This can be limited for high frequency signals such as ECG and rapidly changing signals, so appropriate frequency compensation and filtering design is required. It is hoped that better voltage regulation measures can be found in future experiments, and the influence of bandwidth limitation on the amplification effect of two-stage amplifiers can be reduced.

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