Study on Debugging and Simulation of Low-Frequency Small Signal Amplifier Circuit

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Abstract: To weaken the ordinary CMOS amplifier 1/f noise interference, and amplify this type of signal to a level that can be detected or processed by digital signals, this paper proposes an amplifier circuit design method based on the idea of "modulation-amplification-demodulation", consist of local oscillator unit, mixer unit, amplifying unit and low pass filter unit. And then we used PSpice software to conduct simulation analysis of the entire amplifier circuit, including voltage gain analysis, transient analysis and noise characteristic simulation. The simulation results show that the low-frequency low-noise amplifier designed this time achieves the expected performance indicators.

1. Introduction

With the rapid development of modern science and technology, more and more small signal detection and processing are involved in various fields such as national defense technology, industrial applications, and basic scientific research, such as human electrocardiogram signals, nerve signals, biomagnetic signals, radar echo signals, geological detection reflected wave signals, etc. The signals output by these sensors are very weak, and are susceptible to noise interference. Some of these noise interferences are generated by external noise interference sources, and some are caused by noise from the circuit itself. In order to accurately extract useful signals and facilitate signal analysis and processing, such weak signals must be amplified to hundreds of millivolts or even volts by an amplifier to be effectively processed by some digital instruments.

Low frequency small signal detection is an important part of the micro sensor readout circuit, and also one of the key technologies related to the sensor sensitivity. In this paper, according to the characteristics of the output signal of the micro sensor, an amplifier circuit designed for low-frequency small signal detection is designed, which has higher noise suppression capacity and lower distortion compared with the traditional amplifier.

2. Working Principle of Amplifier Circuit

For low-frequency small signals output by microsensors, high-precision amplification must be performed before display or digital circuit processing, otherwise it will be easily overwhelmed by environmental noise or low-frequency noise of ordinary amplifiers, affecting the sensitivity of the sensor. The expected performance indicators of the low-frequency Small Signal amplifier circuit designed in this paper are as follows:

(1) The circuit can realize closed-loop amplification of more than 100 times, and amplify mV magnitude signals to V level, which is convenient for measurement or display processing;

(2) Low noise, the suppression of common mode noise is more than 10000 times, that is, the noise spectral density is more than 80dB;

(3) The maximum jitter of the amplified signal is within 1%.

The amplifying circuit designed in this paper consists of four parts: local oscillator unit, mixer unit, amplifying unit and low pass filter unit.

Its basic working principle is: first, the low-frequency small signal from the micro sensor is modulated to the local frequency by the mixer; second, amplified by the amplification unit to overcome the 1/f noise interference of ordinary amplifiers; and then, the signal is demodulated to low frequency by the mixer, at the same time, the 1/f noise of the amplification unit is modulated to the

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high frequency region near the local oscillator; as last, a low-pass filter is used to separate the processed signal from the 1/f noise signal, thereby suppressing 1/f noise.

3. Design of Low Frequency Small Signal Amplifier Circuit

3.1. Local Oscillator Unit

This paper adopts an oscillator whose output is a sinusoidal signal, also known as a sinusoidal signal generator. The commonly used sine signal generator has three structures: LC oscillator, crystal oscillator and RC oscillator. There are two disadvantages of LC oscillator: first, the inductance will produce parasitic effects, the theoretical and practical deviations are difficult to estimate; second, the integration of on-chip inductors in analog circuits takes up a large chip area and has poor performance. Crystal oscillators are mainly used for high-frequency applications and can range up to hundreds of megahertz. RC oscillator can be divided into bridge type, double T network type and phase shift type. Among them, bridge oscillator circuit is the most commonly used type at present. In this paper, RC Venturi bridge structure is used, which is self-excited zero phase shift oscillator.

The amplifier in this Venturi bridge oscillator has the same structure as the amplifier in the 3.5 low-pass filter. It uses a single-ended output two-stage operational amplifier with simple structure, high DC gain, and high unity gain bandwidth, as shown in Figure 1.

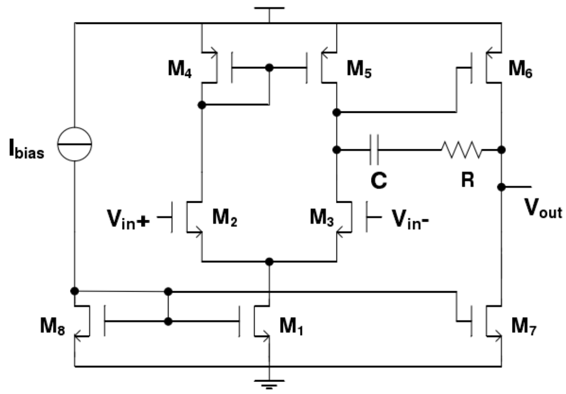

Figure 1. Two-stage operational amplifier circuit diagram.

M_2 and M_3 constitute a differential input stage, forming a differential input stage and convert the input voltage signal into a current signal; M_4 and M_5 are current mirror loads, which convert the current signal into a voltage signal; M_6 and M_7 constitute the second stage of the amplifier; M_7 is a current source load. Miller capacitor C and zero adjustment resistance R are connected between the first stage and the second stage to adjust the zero pole position of the circuit and make the circuit stable.

The working current of two-stage amplifier, full differential amplifier and mixer in the local oscillator unit are all provided by the same bias circuit, as shown in Figure 2.

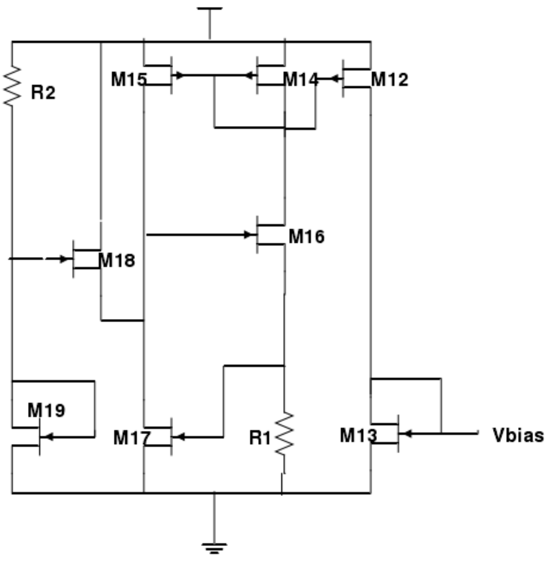

Figure 2. Bias circuit diagram

In order to make the circuit work normally, the first thing is to have a suitable working point. In general circuits, some use transistor voltage division to obtain bias voltage, some use resistance voltage division to obtain bias voltage, but both of them are easily affected by temperature, power supply voltage and process. The whole system is supplied by the same bias circuit, and all bias circuits have the possibility of zero current. In order to avoid this, we add a starting circuit to the system, composed of M_{18}, M_{19} and R_2. Once the circuit starts to work normally, M_{18} of the starting circuit is in the cut-off state, which does not affect the operation of the bias circuit.

3.2. Mixer Unit

Mixer is one of the core units of the whole circuit. Its performance directly affects the accuracy of the output signal and the ability of noise suppression. In order to reduce the noise contribution of the mixer in the whole system and suppress even harmonics, the classical Gilbert cell structure with strong conversion gain, isolation and even harmonics suppression ability is selected in this paper. In order to reduce the deviation caused by parasitic effect, the same structure is adopted for the two mixing, and the same local oscillator unit provides the carrier. The circuit structure of Gilbert mixer unit is shown in Figure 3. It includes three modules: bias circuit, Gilbert unit and voltage follower.

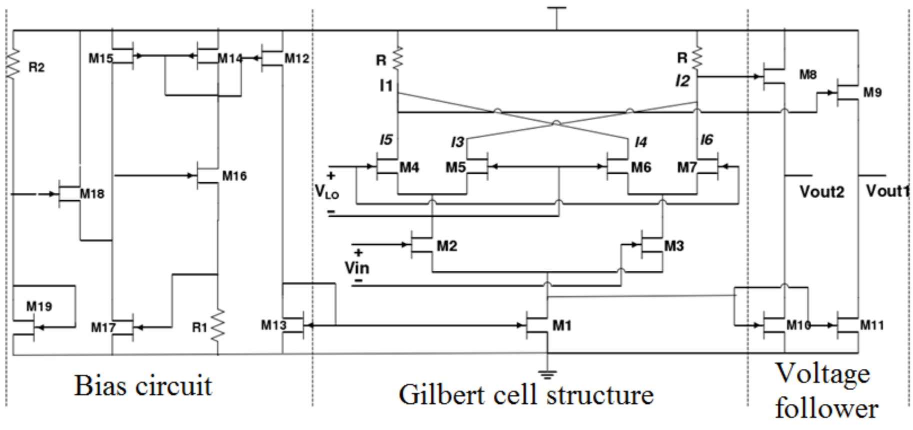

Figure 3. The circuit structure of Gilbert mixer unit

The Gilbert cell structure can be simply divided into three parts: transconductance stage, switch stage and load stage. In order to improve transconductance, MOS transistor works in saturation region. The conversion gain of the mixer depends on the effective transconductance of the transconductor. The thermal noise of the transconductor has a great influence on the noise of the mixer. The design of the transconductor stage parameters plays an important role in the overall performance of the mixer. The resistance R forms the load stage and converts the current signal to the voltage signal output. The transconductance stage and switch stage of the structure form a double balance structure.

Voltage follower has two purposes: one is to ensure the DC signal level of the input signal of the subsequent amplifier or low-pass filter; the other is to provide large driving power considering the influence of the capacitive load of the subsequent circuit. In order to get a good tradeoff between gain, isolation and noise performance, the transistor size must be adjusted repeatedly.

The conversion gain of mixer unit can be expressed as:

$$G_v = 2g_{m^2} \times R \times A$$

In the formula, *A* is the gain of the voltage follower, which is frequency dependent and slightly less than 1.

3.3. Amplification Unit

The amplification unit is the core part of this paper. In order to control the magnification, the closed-loop amplification is used. Considering the requirement of double in and double out pins, a fully differential amplifier is used in this paper. Such structure has the advantages of high gain, large unit gain bandwidth, large output swing and high common mode rejection ratio. The full differential amplifier circuit structure used in this paper is shown in Figure 4, which is divided into bias circuit and amplifier main circuit.

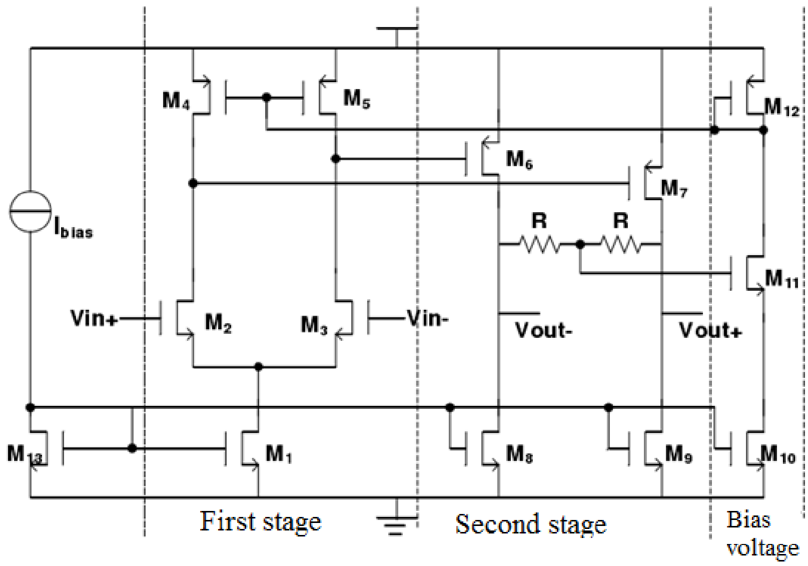

Figure 4. The circuit structure of full differential amplifier.

The amplification circuit is divided into the first stage and the second stage. The first stage mainly provides large gain; the second stage not only provides amplification but also realizes large driving power and large swing. In the circuit structure, M_1, M_2, M_3, M_4, M_5 form the first stage of the fully differential operational amplifier. Among them, M_2 and M_3 constitute a differential input stage that converts a voltage signal into a current signal; M_4 and M_5 constitute a current source load and convert current signals into voltage signals; M_1 pipe determines the current flowing across the conduit, which is called the tail current. M_6, M_7, M_8, M_9 form the second stage of a symmetrical amplifier. Among them, M_8 and M_9 are current source load; M_{10}, M_{11}, M_{12} and R form a bias voltage source and provide bias voltage for the first stage load.

4. Simulation Analysis of Amplifier Circuit

In order to predict the performance of the designed circuit, in this paper, PSpice software is used to conduct simulation analysis of the low frequency small signal amplification circuit. The simulation environment of analog circuit design is divided into three categories: DC analysis, AC analysis and transient analysis.

4.1. Voltage Gain Analysis

We conduct AC small signal analysis on the overall circuit diagram. Differential input terminals in+ and in- input 1mV and 2mV AC small signal differential mode voltage. Scanning signal frequency starts scanning from 1Hz and cuts off to 1.5MHz. Record 10 points every 10 octave, and obtain the voltage gain characteristic curve as shown in Figure 5.

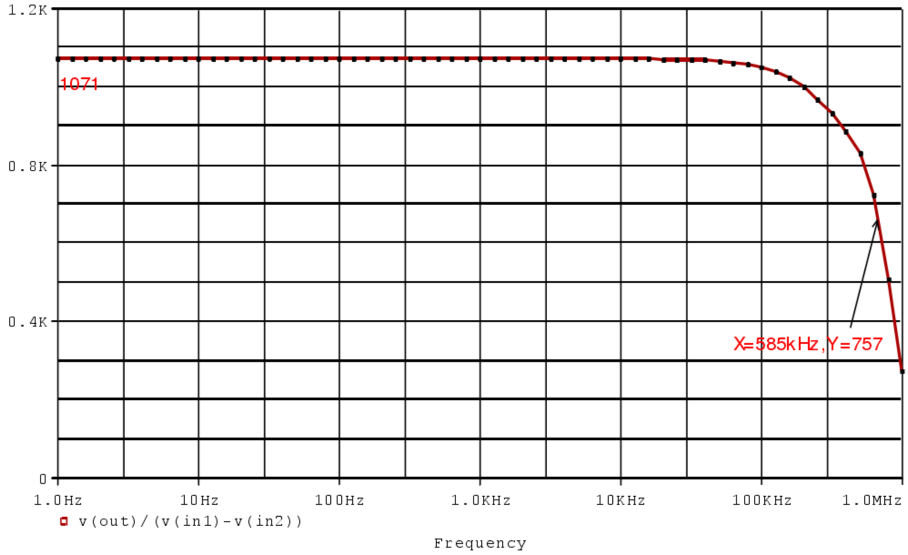

Figure 5. Voltage gain of the amplifier circuit.

It can be seen from Figure 6 that, the small signal voltage magnification of this amplifier circuit is about 1071 times. At a frequency of 100k Hz, the voltage gain can still stabilize at 1050 times. The upper limit cut-off frequency of the amplifier circuit reaches 585k Hz, which satisfies the operating frequency bandwidth required by this design.

4.2. Transient Analysis

Transient analysis is a nonlinear time-domain analysis method that analyzes the transient response at the output of a circuit given an input excitation signal. This transient analysis uses a sinusoidal voltage source and a square wave voltage source as excitation signals to simulate the circuit to obtain the output response of the circuit and analyze whether the circuit is distorted.

Sinusoidal AC small signal with input V_{pp} value of 100μV and frequency of 10k Hz at the differential input. The input waveform is shown in Figure 6.

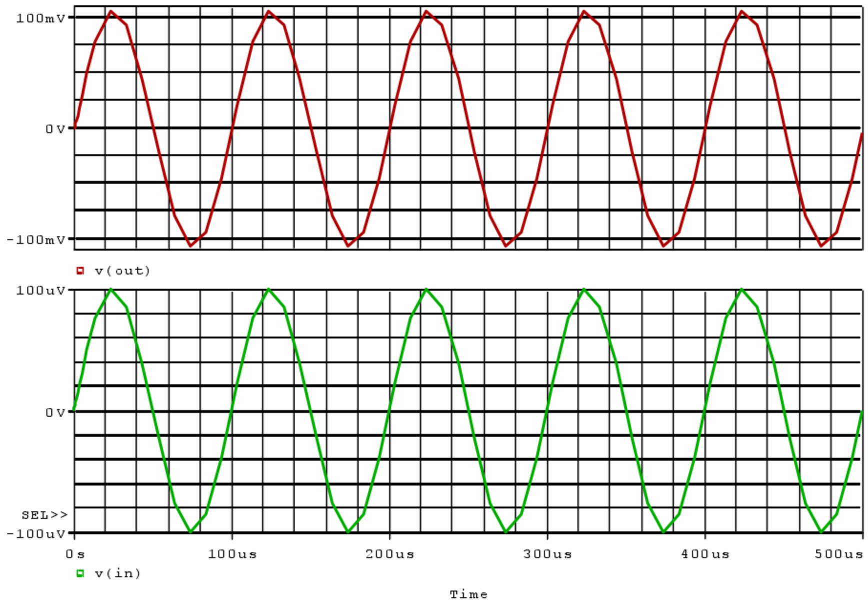

Figure 6. Input and output transient simulation sinusoidal small signal.

Comparing the input and output voltage waveforms, it can be seen that a small sine signal with a peak-to-peak value of 100 μV can be amplified to a sine signal output with a peak-to-peak value of 100 mV, and the voltage waveform has almost no distortion. This reflects that the amplifier can amplify the sinusoidal voltage signal of 100 microvolts almost without distortion. But the output voltage waveform has a certain displacement on the Y axis, which is caused by the output offset voltage.

4.3. Noise Characteristic Simulation

The noise performance of amplifier can be expressed by equivalent input noise. It reflects the noise source inside the whole amplifying circuit, the shot noise and low frequency noise of the semiconductor element in the input terminal. We test the equivalent input noise of the circuit, the simulation results are shown in Figure 7.

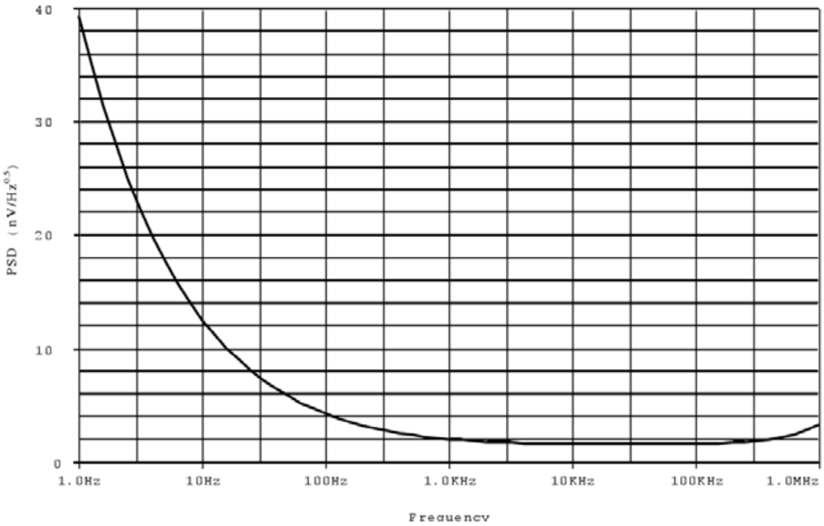

Figure 7. Equivalent input noise of the amplifier circuit.

As shown in Figure 7, the equivalent input noise of the amplifier circuit in the designed operating frequency range is nV level. The equivalent input noise of the circuit is 40 $nV/Hz^{0.5}$ at a frequency of 1 Hz. When the frequency is increased to 10 Hz, the equivalent input noise is reduced to 11 $nV/Hz^{0.5}$. The noise simulation results show that the use of high-precision and low-noise JFET differential pairs as the input device, the low-noise op amp constitutes a negative feedback network amplifier circuit structure can obtain excellent noise parameters, which meets the requirements of design indicators.

5. Conclusion

This paper studies the low-frequency Small Signal amplifier circuit, the purpose is to weaken the ordinary CMOS amplifier 1/f noise interference, and amplify this type of signal to a level that can be detected or processed by digital signals. We propose an amplifier circuit design method based on the idea of "modulation-amplification-demodulation". The circuit includes a Venturi local oscillator unit, a Gilbert mixer unit, a fully differential amplifier unit, and a first-order active low-pass filter unit. And then we used PSpice software to conduct simulation analysis of the entire amplifier circuit, including voltage gain analysis, transient analysis and noise characteristic simulation. The simulation results show that the low-frequency low-noise amplifier designed this time achieves the expected performance indicators.

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