Proceedings of the 3rd International Conference on Computing Innovation and Applied Physics
DOI: 10.54254/2753-8818/14/20240912

Improving noise levels based on amplifier structure analysis

Yipeng Hu

130028,School of physics, Changchun University of Science and Technology, Chaoyang District, Changchun City, Jilin Province, China

18186897231@163.com

Abstract. As the core component of electronic circuits, amplifiers play a pivotal role in fields such as communications, medical care, audio processing, instrumentation, scientific research and military technology. However, the noise problem of the amplifier has a direct impact on the reliability and accuracy of the system, how to reduce the impact of noise is crucial. This paper aims to study and solve noise problems in amplifier design. The first part focuses on the design of operational amplifiers. By adjusting the circuit structure and introducing current mirrors, the noise of the input and output stages is successfully reduced and the amplifier performance is improved. The second part focuses on the design of instrumentation amplifiers, introducing kT/C noise elimination technology, chopper modulation structure solves the noise and aliasing problems in switched capacitor instrumentation amplifiers and improve performance.

Keywords: Noise, Current Mirror, Chopper Modulation, Three-op Amplifier.

1. Introduction

Amplifiers are indispensable components in electronic circuits, and their applications widely cover various key fields such as communications, medical care, audio processing, instrumentation [1], etc. In the field of communications, amplifiers are used to enhance the transmission range and quality of signals, and medical equipment also requires high-quality amplifiers to collect and process physiological signals, such as electrocardiogram and MRI equipment [2]. In the field of audio processing, amplifiers are used to ensure high-fidelity sound effects, which affects our listening experience in music, movies, and games. Instrumentation requires high-precision amplifiers to ensure measurement accuracy. In scientific research and military technology, amplifiers are widely used to process various signals to meet scientific experiments and mission requirements, including particle accelerators, radar [3], satellite communications, etc. The applications of amplifiers cover many fields such as scientific research, laboratory measurement and industrial applications. With the rapid development of modern information technology and the promotion of the Internet, artificial intelligence, autonomous driving and other fields, the public demand for amplifiers for sensor networks and signal processing is also increasing. For example, self-driving cars require up to hundreds of sensors to sense the surrounding environment and closely connect the physical world with the network control; sensor applications have expanded to many fields such as industrial production, resource exploration, and medical diagnosis [4].

However, despite significant advances in integrated circuit technology, amplifier design still faces new challenges,it requires to adapt to special requirements in different fields, such as low power consumption, high performance, mobility, etc. In these areas, the performance and noise characteristics of the amplifier are directly relevant to the reliability, accuracy and efficiency of the system. Amplifier noise mainly includes thermal noise, 1/f noise (also called low-frequency noise or drift noise), input noise [5], etc. These noise sources can come from the device itself, environmental interference, and the design of the amplifier circuit. Thermal noise is caused by thermal movement within components and is related to temperature and resistance [6].1/f noise is noise that is inversely proportional to frequency. It dominates the low-frequency band and often affects the performance of low-frequency amplifiers. Input noise is random fluctuations in the input signal that can be reduced by modifications to the signal source. In order to reduce amplifier noise, predecessors have adopted a variety of methods, including selecting low-noise components, improving the circuit topology, and optimizing the working conditions of the amplifier [7]. Different amplifier structures have different effects on noise suppression. Therefore, in-depth study of the noise characteristics of these structures is crucial to improve amplifier performance. Noise suppression has therefore become a crucial challenge in amplifier design.

The subject of this paper is amplifier noise reduction. The research is mainly conducted on two practical studies. In the first study, the traditional operational amplifier architecture is optimized to meet the key parameter requirements of the operational amplifier in the partial discharge detection circuit. To solve the problem, a folded cascode structure, the noise reduction structure and simulation results of three operational amplifiers are given. In the second study, for the noise reduction problem of instrument amplifier research, the noise time threshold diagram was obtained through low-frequency following and high-frequency suppression methods, and the noise was preliminarily sorted, and then chopper modulation was used to make the low-frequency components of the noise voltage positive and negative. Negatives cancel each other out, thus eliminating noise.

This paper is divided into five parts: First part is an introduction, which introduces the application background of amplifiers, the causes of noise and the importance of eliminating noise.Second part introduces low-noise design methods for operational amplifiers. The third part introduces how instrumentation amplifiers perform the noise reduction. The fourth part is the experimental results and analysis, which analyzes the data obtained from the two different experimental methods. The fifth part is a summary, containing the research results and prospects for future noise reduction in amplifiers.

2. Design of low-noise operational amplifier

Optimize the traditional operational amplifier architecture to meet the key parameter requirements of the operational amplifier in the partial discharge detection and conditioning circuit. Text chose the folded cascode structure, the output noise of the output stage, and the noise reduction structure of the three-op amp instrumentation amplifier to solve the problem.

2.1. Noise processing for input stage folded cascode structure

The main structure of the op amp adopts a folded cascode circuit as shown in Figure 1.

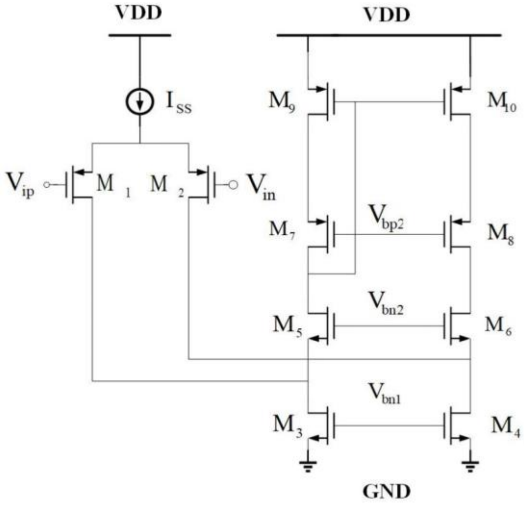

Figure 1. Folded cascode circuit.

In the figure, since the current mirror of M3M4 that provides small signal flows through the maximum current, a large amount of noise is generated. By calculating the equivalent input noise in the circuit:

$$\overline{V^2{}_{n,in}} = 8kT \cdot \frac{2}{3}\left(\frac{1}{g^2{}_{m1,2}} + \frac{g_{m3,4}}{g^2{}_{m1,2}} + \frac{g_{m9,10}}{g^2{}_{m1,2}}\right) + 2 \cdot \frac{1}{C_{ox} \cdot f}$$
$$\cdot \left(\frac{K_p}{WL_{1,2}} + \frac{K_N}{WL_{3,4}} \cdot \frac{g_{m3,4}}{g^2{}_{m1,2}} + \frac{K_p}{WL_{9,10}} \cdot \frac{g_{m9,10}}{g^2{}_{m1,2}}\right)$$

It can be seen that it can be achieved by increasing gm1, 2, decreasing gm3, 4, and gm9, 10. The reduction of the latter is a compromise between power consumption and area and noise, which needs to be achieved by increasing the input tube current and reducing the overdrive voltage. To this end, the current mirror needs to be divided into two current mirrors to reduce the noise as shown in the Figure 2:

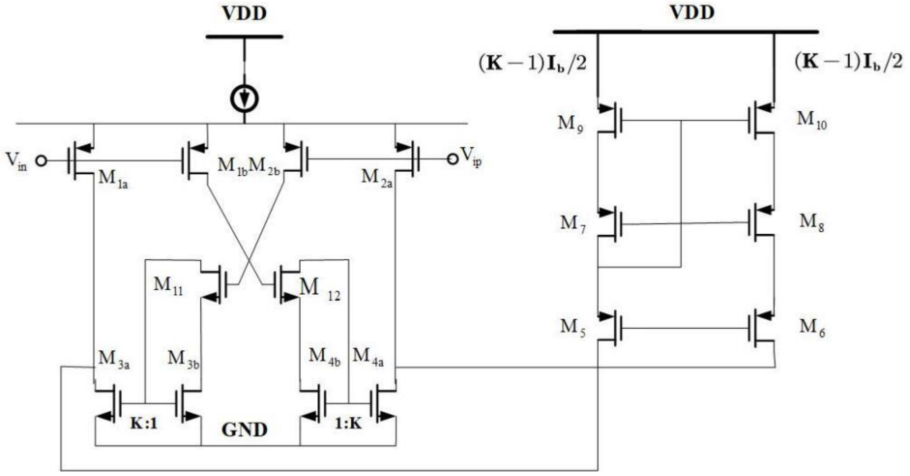

Figure 2. Current splitting folded cascode circuit.

M2 is divided into identical M1a and M1b. M3 and M4 are divided into two identical current mirrors, and the width-to-length ratio is K to 1. The equivalent input noise of the circuit is:

$$\overline{V^2_{n\,in}} = 8kT \cdot \frac{2}{3} \cdot \left(\frac{1+k^2}{g^2_{m1a,2a} \cdot (k+1)^2} + \frac{g_{m3a,4a}}{g^2_{m1a,2a}} \cdot \frac{1}{k+1} + \frac{g_{m9,10}}{g^2_{m1a,2a}} \cdot \frac{1}{(k+1)^2}\right)$$
$$+ 2 \cdot \frac{1}{C_{ox} \cdot f} \cdot \left(\begin{array}{c} \dfrac{K_p \cdot (1+k^2)}{WL_{1,2} \cdot (k+1)^2} + \dfrac{K_N}{WL_{3,4}} \cdot \dfrac{g^2_{m3,4}}{g^2_{m1,2}} \cdot \dfrac{1}{k+1} \\ + \dfrac{K_p}{WL_{9,10}} \cdot \dfrac{g_{m9,10}}{g^2_{m1,2}} \cdot \dfrac{1}{(k+1)^2} \end{array}\right)$$

It can be seen that the equivalent input noise of the operational amplifier is reduced.

2.2. *Processing of output stage output noise*

Use an enable circuit to allow the circuit to control whether to operate an amplifier through the power supply voltage or ground voltage, thereby avoiding output noise caused by incomplete reference voltage establishment after power-on.

The complete operational amplifier circuit shown in Figure 3:

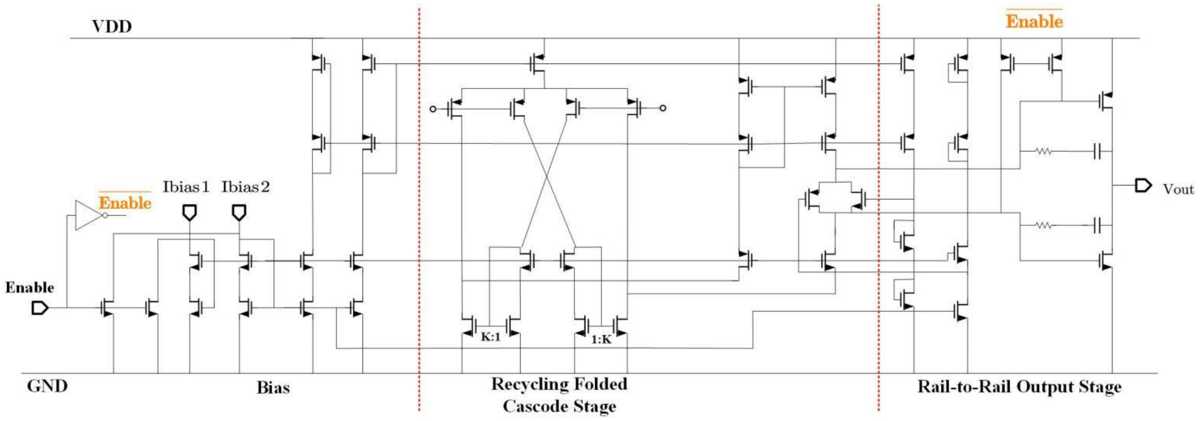

Figure 3. Detailed circuit structure of high-speed, low-noise operational amplifier.

The structure on the left is the enable control port, the middle is the split cascaded code structure, and the structure on the right is a rail-to-rail output stage. The structure of the operational amplifier is as follows:

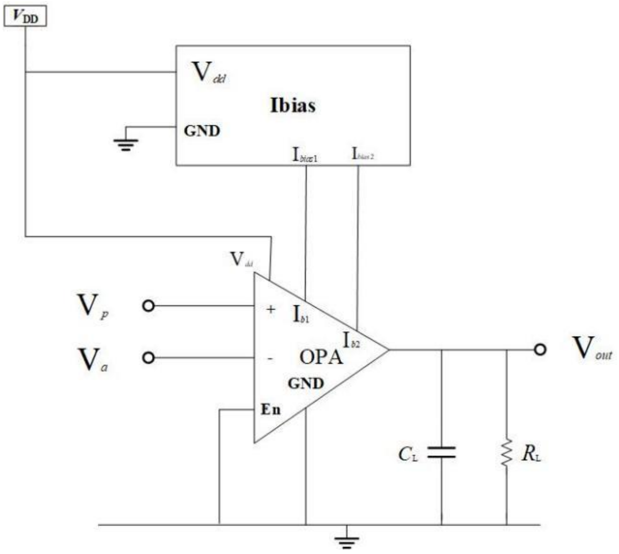

Figure 4. Basic simulation circuit of operational amplifier.

The current-split structure not only helps achieve low noise but also increases speed. Considering power consumption, we adjusted the ratio of transconductance so that the gain-bandwidth product of the RFC structure under the same power consumption is twice higher than that of the traditional structure, that is, the speed is increased by two times. In addition, the output impedance of the RFC structure is larger, which makes its DC gain 8-10dB higher than the traditional structure, with better linearity and power supply rejection ratio.

In the equivalent input noise simulation circuit, the op amp is connected to a unit negative feedback structure, the positive terminal is connected to a 600mV DC voltage, and the output is connected to a load of a 20pF capacitor and a 2k resistor in parallel. Through cadence's noise simulation, we can get the input terminal voltage noise frequency density distribution, as shown in the Figure 5:

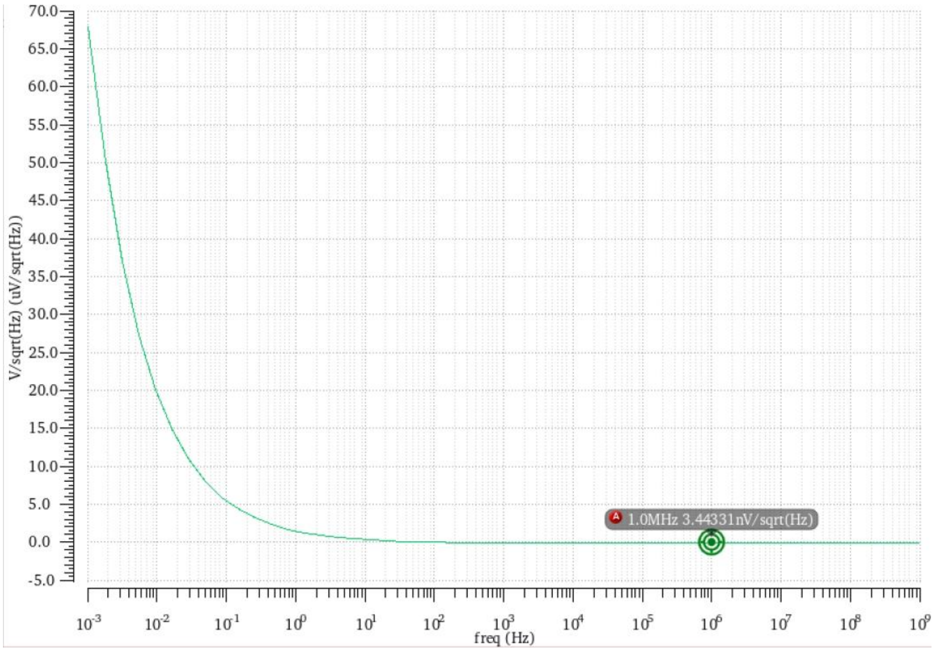

Figure 5. Equivalent input noise simulation results of op amp [8].

Through cadence's noise simulation, we can get the frequency and density distribution of the input voltage and noise, that is, the equivalent input noise of the ordinary op amp is 16.36HZ, while the noise of the improved op amp is 3.44HZ.

2.3. *Noise processing of three-op amp instrumentation amplifier*

Instrumentation amplifier has the advantages of low noise, high input impedance, low output impedance, high common mode rejection ratio and stable and accurate gain. It is a kind of differential amplifier and is divided into single-op amp instrumentation amplifier, dual-op amp instrumentation amplifier, and three-op amp instrumentation amplifier.

Compared with single op amp and dual op amp, three-op amp amplifier has various advantages. The three-op amp amplifier used in this article is shown in the Figure 6:

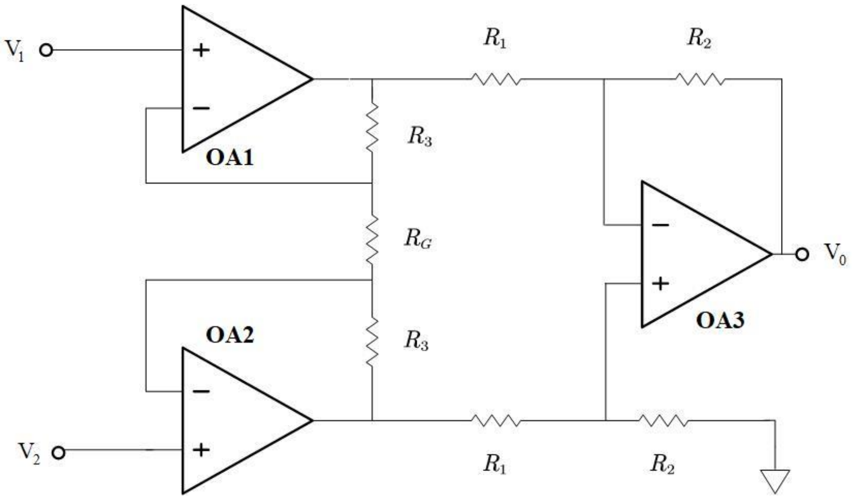

Figure 6. Three-Op Amp Instrumentation Amplifier.

In order to reduce the impact of noise, OA1, OA2, and OA3 all use high-speed, low-noise operational amplifier models, shown in Figure 7 below:

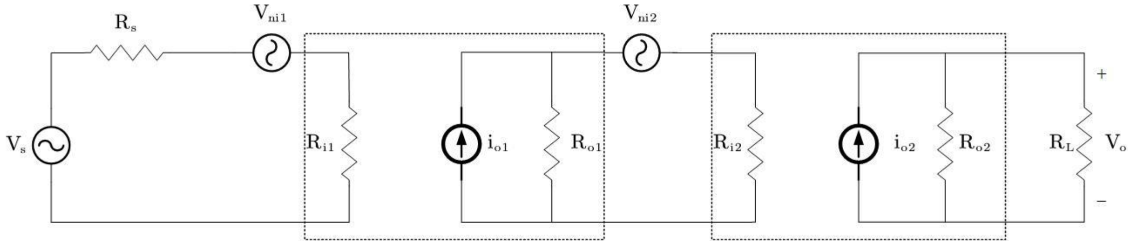

Figure 7. Multistage amplifier noise model.

The gain was concentrated in the input stage, and the noise simulation was performed on the three-op-amp instrumentation amplifier. The measured noise at 1MHz was 143.04nV/√Hz, which met the requirements.

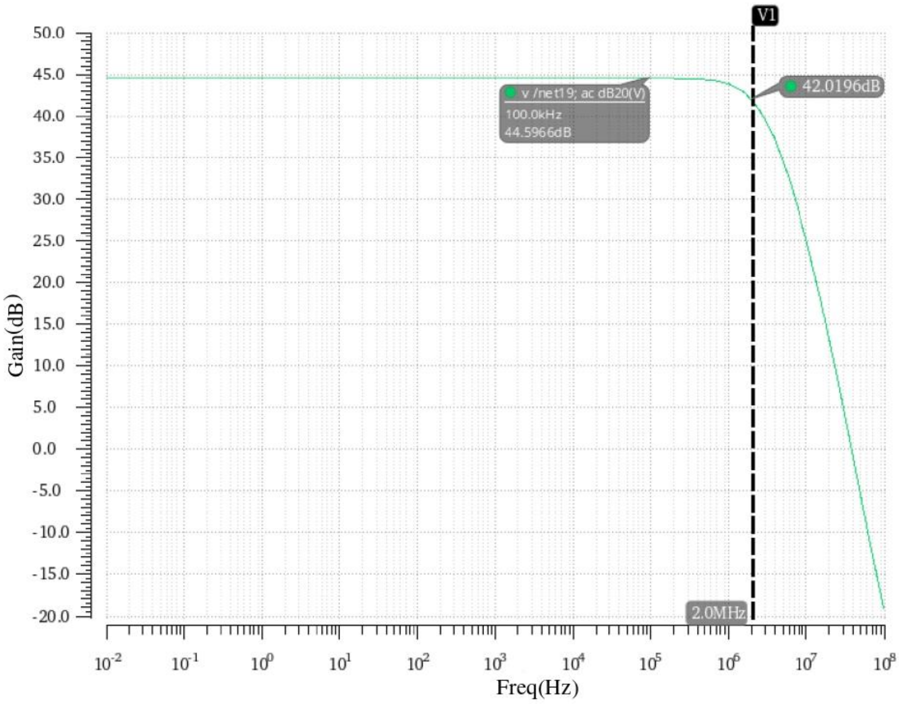

Figure 8. Three-Op Amp Instrumentation Amplifier Frequency-Gain Curve [8].

3. Noise reduction design for low-noise high-gain instrumentation amplifier research

Capacitive instrumentation amplifiers based on switched capacitor discrete-time technology commonly suffer from noise mixing kT/C noise elimination technology and chopper modulation structure can improve the performance of this circuit to solve the defects of switched capacitor circuits.

3.1. kT/C noise cancellation technology

A simple CMOS sample and hold circuit is shown in Figure 9. The circuit consists of an NMOS tube and a sampling capacitor Cs. The NMOS tube serves as a switch and is periodically controlled by the clock CK. The clock period is Ts and the conduction duty cycle is m. Assume that the input signal changes little and operates near low voltage. When the clock CK is high level, the switch is turned on to form a low-pass filter, which limits the signal bandwidth to below 1/Ron•Cs to achieve low-frequency following and high-frequency suppression. . When the clock CK is low, the switch is turned off and the sampled value on the capacitor Cs is maintained until the next high clock arrives.

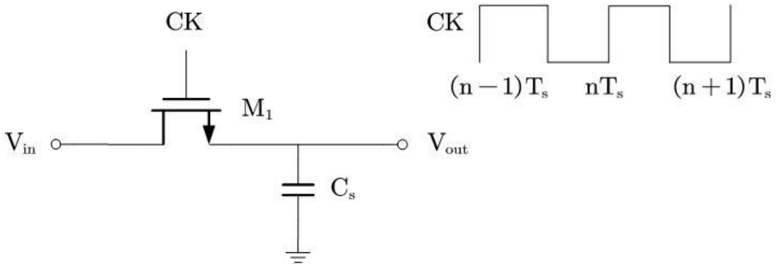

Figure 9. Basic CMOS sample and hold circuit.

The kT/C noise elimination technology proposed in this chapter is a noise shaping technology based on the kT/C noise transformation mechanism, targeting the holding process and combined with chopper modulation technology. First of all, it is usually assumed that the Nyquist frequency of the signal of interest in engineering is far lower than the sampling frequency f_s, that is, this technology is only suitable for low-frequency signal processing. The noise transformation mechanism diagram is as follows:

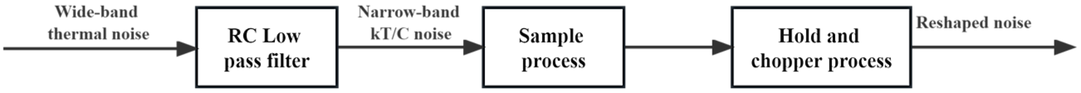

Figure 10. Construction of vh(t) noise transformation mechanism model.

In extreme cases, the sampling conduction duty cycle m→0, the signal $V_{kT/C}(t)$ on the sampling capacitor Cs is sampled, and then the holding voltage vh(t) is formed in a short period of time. At this time, the thermal noise introduced by the switch on-resistance will affect the output noise power spectral density function. The power spectral density function of the output noise of the noise through the sample and hold circuit is when the on-duty ratio m→0:

$$S_{v_h}(\omega)|_{m\rightarrow 0} = Sinc^2\left(\frac{\omega T}{2}\right)\cdot T_s\cdot\frac{kT}{C_s}$$

Then, the holding voltage vh(t) of the positive-phase output is flipped once, and then flipped again after a time of (1-m)Ts/2. This causes the noise voltage to undergo repeated chopper modulation, so that the chopper frequency f_{ch} is the same as the sampling frequency fs, and the noise voltage vh&ch(t) after chopper modulation is obtained.

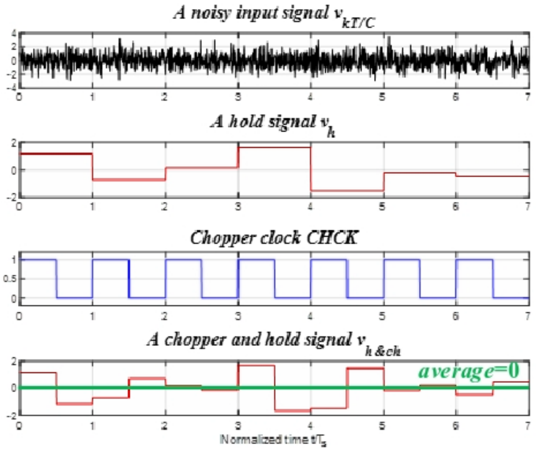

Figure 11. Time domain diagram of noise voltage before and after kT/C noise elimination [9].

When observed in the time domain, when the band-limited kT/C noise is sampled on the sampling capacitor Cs, the noise voltage at this time can be seen as a tiny DC component. During the hold process, the noise voltage undergoes chopper modulation, the low-frequency component of its output continuous noise voltage is offset by one positive and one negative, and its mean value is 0.

3.2. Main amplifier noise optimization

When this article adopts the fundamental frequency kT/C noise elimination technology, the switched capacitor instrumentation amplifier successfully solves most of the noise problems. Except for some continuous thermal noise and the internal low-frequency noise of the main amplifier, other noise can be almost ignored.

In order to further improve the noise performance, the article introduces source-level resistor negative feedback (as shown in Figure 12). In this step, the 1/f noise and thermal noise of MOS tube M4 is reduced through high gain gm4•R, leaving only the thermal noise of the resistor as the main contribution to the output noise. Resistor R generates almost no 1/f noise, and its thermal noise power efficiency is significantly higher than that of MOS tubes. The input equivalent thermal noise power spectral density of the MOS pair of transistors M1 and M4 and the resistor pair R in the main amplifier designed in this article is:

$$v_{n\,MA}^{2}=\frac{K_{FN}}{C_{ox}^{2}WL}\times\frac{1}{f_{ch\,1A}^{\alpha}}+\frac{2nkT}{g_{m1}}$$

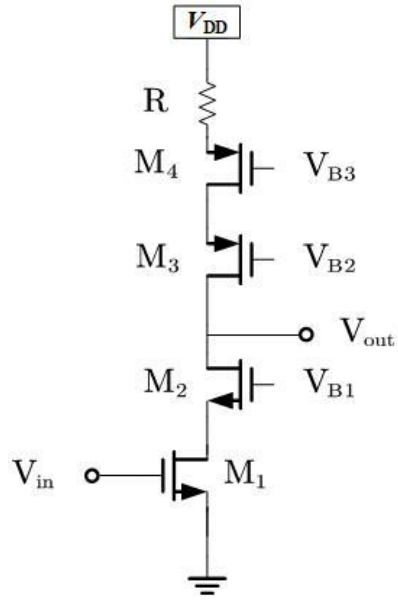

Figure 12. Source resistance negative feedback.

When increasing the source resistance R, increasing the input transconductance gm1 of the transistor M1, and reducing the product gm4•R of the source resistance and the transconductance of the M4 transistor, the input equivalent thermal noise of the main amplifier can be reduced.

In the design, the source negative feedback resistor R=6kΩ is selected, the compensation capacitor CC is about 3pF, and the transconductance gm1 of the input NMOS pair tube working in the sub-threshold region is 1.3mS. Using Cadence to simulate the performance of the main amplifier, its open-loop DC gain is greater than 136-dB at each process angle, and the unit gain bandwidth (Unity Gain Bandwidth, UGB) is greater than 37.5-MHz. Under the load capacitance C_L=2-pF,the phase margins are all greater than 56°, and the input equivalent noise at the chopper modulation frequency f_{ch_IA} is 100-kHz is less than 4.5-nV/√Hz (Figure 5.14), further improving the performance of the overall system.

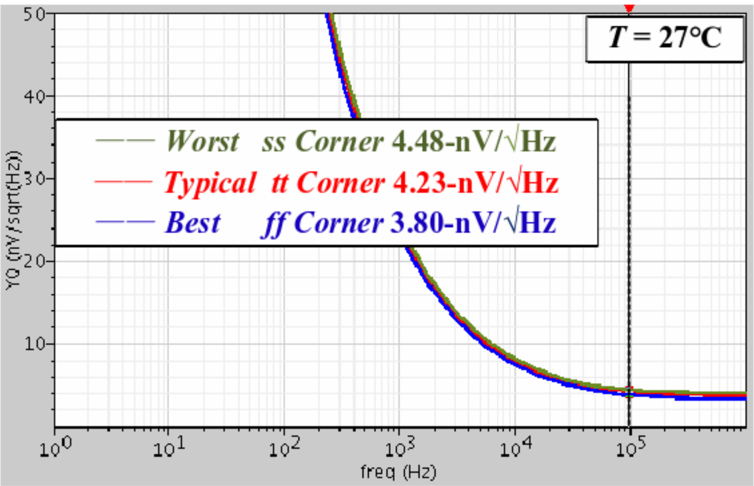

Figure 13. Input equivalent noise at main amplifier chopper modulation frequency [9].

4. Analysis of results

The first study is the design of an operational amplifier. It mainly deals with the noise of the folded cascode structure of the input stage and the output noise of the output stage. It adopts the method of adjusting the pipeline transconductance and introducing a current mirror to reduce the noise of the input stage and the output stage.

The second study give priority to the design of instrumentation amplifiers, using switched capacitor technology and noise optimization of the main amplifier to cope with different application requirements. It introduces kT/C noise elimination technology, uses chopper wave modulation technology to solve the noise problem of switched capacitor instrumentation amplifiers.

The application scenarios need to be clearly designed. If it is an instrument application that requires high-precision measurement, then the method in the second article is more suitable. If it is a general-purpose operational amplifier, the method in the first article may be more applicable. Both articles emphasize the importance of noise sources, but they may need to be considered more comprehensively during the design process to identify the most critical noise sources and reduce their impact in a targeted manner. Spectrum analysis is mentioned in the second article, and the first article can also provide a more in-depth noise spectrum analysis [10] to determine the frequency domain characteristics and impact on the design. Consider adopting emerging noise reduction technologies such as adaptive filtering, digital signal processing, etc. To further improve performance.

5. Conclusion

The paper focuses on the noise reduction design of amplifiers and discusses two practical cases. The first case focuses on the design of low-noise operational amplifiers. By optimizing the traditional operational amplifier architecture, using a folded cascode structure, and a noise reduction structure of a three-op amp amplifier, the amplifier's input and output effective noise is successfully reduced, making it more suitable for applications such as partial discharge detection and conditioning circuits. In the second case, the noise reduction design of a low-noise, high-gain instrumentation amplifier was studied, and kT/C noise elimination technology and charge injection effect compensation technology were introduced to effectively suppress the noise aliasing problem in switched-capacitor instrumentation amplifiers, optimizes the performance of the main amplifier and enables it to exhibit excellent performance under various process conditions.

In the design of the first operational amplifier, by adjusting the pipe transconductance and introducing current mirrors, the noise of the input stage and the output stage can be significantly reduced, thereby improving the performance of the amplifier. This has important practical implications for applications requiring high-precision signal processing, such as partial discharge detection. In the second instrumentation amplifier, kT/C noise elimination technology and chopper modulation structure is used to effectively improve the performance of the switched capacitor instrumentation amplifier. This enables the amplifier to exhibit higher performance in broadband signal processing.

For the future, new noise reduction technologies and methods, such as Low noise chopper amplifier with adaptive filtering and digital signal processing [11], can be further explored to further improve the performance of amplifiers. The field of amplifier design still has broad research prospects and challenges, and will continue to promote the development of electronic circuits and instrumentation technology.

References

[1] Mohebi Z, Parandin F, Shama F, et al. Highly linear wide band low noise amplifiers: A literature review (2010–2018) [J]. Microelectronics Journal, 2020, 95: 104673.
[2] Kouhalvandi L, Matekovits L, Peter I. Amplifiers in Biomedical Engineering: A Review from Application Perspectives [J]. Sensors, 2023, 23(4): 2277.
[3] Yadav R, Yadav R, Mishra R. High output power CMOS differential power amplifier for front-end automotive radar application [J]. Sādhanā, 2023, 48(3): 98.
[4] Marzorati D, Mainardi L, Sedda G, et al. MOS sensors array for the discrimination of lung cancer and at-risk subjects with exhaled breath analysis [J]. Chemosensors, 2021, 9(8): 209.
[5] dos Reis C A. A Review of Offset and Noise Reduction Techniques for CMOS [J]. Journal of Integrated Circuits and Systems, 2022, 17(1): 1-9.
[6] Luo D, Zhang M, Wang Z. A low-noise chopper amplifier designed for multi-channel neural signal acquisition [J]. IEEE Journal of Solid-State Circuits, 2019, 54(8): 2255-2265.
[7] dos Reis C A. A Review of Offset and Noise Reduction Techniques for CMOS [J]. Journal of Integrated Circuits and Systems, 2022, 17(1): 1-9.
[8] Haojie Wang. Design of Low Noise Operational Amplifier & Application in Conditioning Circuits of Partial Discharge Detection [D].Zhejiang University,2022.000218.
[9] Shizhe Wang. Research on Low Noise and High Gain Instrumentation Amplifiers and their Switched Capacitor Realizations [D].Zhejiang University,2021.002015.
[10] Zhibin Gao,Hongmin Jiang,Zhihong Liu.Effect of Tread Pitch on Low Rrequency Noise of Tire. [J].Machine design and manufacturing.2022.09.029.
[11] Shad E, Molinas M, Ytterdal T. A Low-power and Low-noise Multi-purpose Chopper Amplifier with High CMRR and PSRR [C]//2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC). IEEE, 2020: 3998-4001.