Interface to the Analog World

Liyuan Liu and Zhihua Wang

1 Sensoring the World

Sensors or detectors are ubiquitous in the world. Everyday millions of them are produced and integrated into various kinds of systems, e.g. TV set, refrigerator, smart phone, PC, laptop, elevators, automobile, plane and so on. With sensors electronic systems can see the world, feel the world and react with the world. With sensors electronic systems seems to be alive and they become much smarter than ever before which makes our daily life more convenient and more comfortable. Sensors are devices which can convert physical or chemical quantities, e.g. luminous intensity, temperature, air pressure, acceleration, height, distance, weight, sound pressure, PH value and so on into signals which can be measured, acquired, processed and stored easier. Nowadays such signals are always electric signals like voltage, current or frequency thanks to the development of modern microelectronics techniques.

Ideal sensors output signals which are proportional to the measurement or to some simple mathematical function of the measurement. The ratio between the output and the input is called sensitivity of the sensor. It means how large the output is if a unit quantity of the input signal is apply to the sensor. However real sensors usually have various non-idealities which makes their characteristics different from the ideal one. In order to characterize such deviations, some parameter of the sensors must be introduced.

- **Sensitivity error** is defined as deviation of sensitivity in practice from the value specified. Usually if the sensor is still linear, such error can be calibrated by simple mathematic manipulation in the post signal processing flow.

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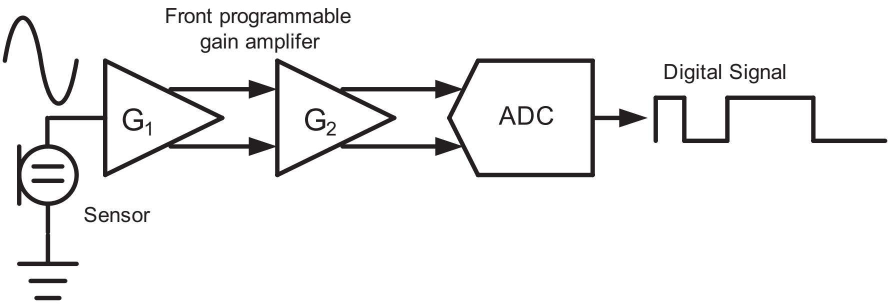

Fig. 1 Analog front end circuits for weak signal conditioning

- **Non-linearity** exists if the sensitivity is not constant and has relations to the input signal. This error can also be adjusted as long as the real characteristic of the sensor can be obtained.
- **Offset** is defined as the output value when zero input is applied to the sensor. Usually the offset is a constant value and can be eliminated by the system calibration procedure.
- **Drift** exists if properties of a sensor varies with time or other ambient factors. The term long time drift usually indicates slow property degradation of a sensor over a long period of time.
- **Linear Range** is defined as a range in which the non-linearity error of the sensitivity can be negligible. The linear range is relied on the specification of the system requirement.
- **Full scale range** is defined as range between the minimum and maximum output values of a sensor. Usually the output of a sensor reaches a limit if the input signal exceeds specified range.
- **Hysteresis** is an error caused by when the measured property reverses direction, but there is some finite lag in time for the sensor to respond, creating a different offset error in one direction than in the other.
- **Noise** is random fluctuation of the sensor output over measurement time.

2 Weak Signal Conditioning

The output voltage or the current signal of a sensor is usually small. Taking MEMS microphone (commonly used sensor for acoustic system) as an example, the maximum output voltage of the microphone is on the order of ~250 mV. Usually the system requires the signal dynamic range be larger than 90dB which means the minimum voltage to be processed is less than 10 μV. To process such a weak signal the following analog front end circuits are preferred as shown in Fig. 1. The signal from the sensor is firstly amplified and then digitized by the analog-to-digital converter (ADC). The pre-amplifier can greatly enhance the signal level of the output of the sensor and relaxes the design requirements of the ADC. However the design of pre-amplifier becomes the bottleneck. Several design issues must be taken into considerations.

- **Noise** may be the most important design issue to be considered in the front end circuits design. The output signal of the sensor is usually low frequency varied signal. At low frequency range, the $1/f$ noise of the circuit is significant especially in CMOS circuits. Although several techniques such as chopping stabilization (CS), correlated double sampling(CDS) and auto-zero(AZ) have already been proposed to effectively remove the low frequency $1/f$ noise, not all the cases are suitable to apply such techniques. Also taking signal conditioning circuits after MEMS microphone as an example, the output impedance of the sensor is quite large which means the driving ability of the sensor is poor. If any of the CS, CDS or AZ is applied, the fast switching network which is necessary in the above techniques will disturb the output of the sensor and even force the sensor into abnormal work conditions. As a result the only way to reduce the $1/f$ noise is by properly sizing the transistors in the amplifier. Large transistor size may result into large chip area and large parasitic which is harmful to the stability of the amplifier.
- **Power consumption** is another important factor in designing front end circuits. In many portable devices and biomedical devices, the energy resource is usually a small battery which is mandatory in order to reduce the volume and weigh of the devices. To extend the battery life, low power circuits design techniques are necessary. The power consumption of the pre-amplifier is determined by two factors. One factor is the noise. The required thermal noise level determines the minimum current of the input stage. Besides the input stage, the amplifier also has output stage to provide enough current sinking and sourcing ability to drive the sampling network of the analog-to-digital converter.
- **Driving and anti-alias noise folding** Sampling the output of the pre-amplifier may lead to noise folding which can raise the noise level in the baseband. To overcome the problem the pre-amplifier must be band limited. However limited bandwidth may slow down the speed of the amplifier and as a result, the settling performance of the amplifier will be degraded. To solve the problem, an RC anti-alias filter can be inserted between the pre-amplifier and the ADC. This filter can also serve as a low power buffer. The reason is that, when ADC starts to sample the output of the RC filter, the sampling capacitor is firstly connected to the capacitor of the filter and charge sharing happens before the pre-amplifier starts to settle. If this capacitor is large enough, the sampling capacitor can soon reach to an initial value near to the final value and the amplifier only needs to compensate the difference and so the current consumption requirement as well as the power consumption requirement can greatly be reduced.

3 Driving the World

With various sensors, the electrical systems can gather information from the ambient and then pass the information to its powerful digital signal processing engine. After processing, the systems should also react with the ambient. Some systems only need to give out digital signal and other devices can receive the signal and makes further processing step. However some other systems need to gives out analog signal in order to drive other devices which can converter the electric signals back into physical signals. For example, in acoustic systems, after signal processing, the system should drive the receiver which can convert the digital signal back into sound. The receiver usually has low input impedance in order that the energy received is large enough. To drive this low impedance receiver, the output stage of any electrical systems must have enough current sinking and sourcing ability. Class-A amplifier has good linearity but the standby current is quite large so as to provide enough transient current. Its power efficiency is low which is not suitable for many low power conditions. Class-AB amplifier can keep the standby current to a very small value. But the circuits design is relative complex and dedicate feedback loop must be designed to stabilize the quiescent current. Class-D amplifier has no standby current and is the most power efficiency output driver architecture. The output of such amplifier may be pulse-width-modulation (PWM) signal or pulse-density-modulation (PDM) signal. The receiver must have sufficient filtering ability so that high frequency noise introduced by sharp 0-1 or 1-0 transition in PWM or PDM signals can be suppressed.

Low Noise Low Power Amplifiers

Shupeng Zhong and Nianxiong Nick Tan

In the applications of high precision, most signal bandwidth is not very wide, several Kilo Hertz or even smaller. But the signal is sometimes too weak to be quantified by Analog-to-Digital converters (ADCs) directly due to the inherent noise of any ADCs, including KT/C noise, flicker noise, thermal noise, etc. So a low noise amplifier is needed before ADCs. As with most design, power dissipation is of great importance. To amplify very week signal with ultra low power is challenging. In this chapter, we will discuss how to design an ultra-low power low noise amplifiers for narrow-band applications.

1 Noise in a Chip

The main noises in a low noise amplifier are flicker noise and thermal noise. There are several sources that can contribute to the noise in a chip [1].

1.1 Flicker Noise

For narrow band signal application, the flicker noise is usually the most significant noise source in an amplifier. The noise power can be expressed roughly by the following equation.

$$V_n^2 = \frac{\mathrm{K}}{\mathrm{C_{ox}WL}} \frac{1}{\mathrm{f}} \tag{1}$$

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Where K is a process-dependent constant. W, L is the MOSFET's size, C_{ox} is the unity capacitance of gate oxide. So the flicker noise is inversely proportional to the frequency and MOSFET's area. In some low frequency application like 50 Hz signal, the flicker noise could be as high as several uV/sqrtHz with a nominal MOS size. This noise can be decreased by enlarging the area of MOSFET, but even 100 times larger area can only reduce the noise power by a factor of 10. Too big transistors will also increase the power dissipation besides increasing the die size.

1.2 Thermal Noise

Unlike flicker noise, the noise spectrum is flat, so it is also called white noise. The noise power density is much lower than flicker noise in low frequency. In CMOS integrated circuits, two kinds of thermal noise need to be considered, which are thermal noise come from physical resistors and thermal noise from MOSFETs.

Resistor Thermal Noise

The noise power can be expressed by

$$V_n^2 = 4\mathrm{kTR} \tag{2}$$

where K is bolzman constant, T is the absolute temperature, and R is the resistance.

As it can be seen, the thermal noise power is proportional to temperature and resistor value. So the only way to decrease the noise is to lower the value of resistor.

MOS Thermal Noise

The noise power can be expressed by [2]

$$V_n^2 = \frac{4\mathrm{kT}\gamma}{\mathrm{g_m}} \tag{3}$$

Where K is bolzman constant, T is the absolute temperature, γ is a process related constant, and g_m is the MOSFET's transconductance.

As can be seen, the thermal noise is proportional to temperature and inversely proportional to MOSFET's transconductance. The transconductance could be expressed to be

$$g_m = \sqrt{2\mathrm{u_n C_{ox}} \frac{\mathrm{W}}{\mathrm{L}} \mathrm{I_d}} \tag{4}$$

Where I_d is the drain current of MOS device, So larger g_m means smaller thermal noise, also means more power consumption.

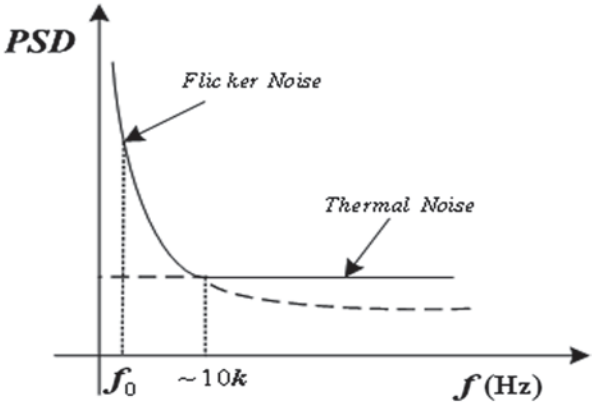


Fig. 1 Cross point of flicker noise and thermal noise

The combination of flicker noise and thermal noise in a typical MOS circuit is shown in Fig. 1. The cross point of flicker noise and thermal noise is normally locating at around 10 kHz, depending on the design and foundry process.

2 Offset and Low Frequency Noise Cancellation

There are several methods to decrease the noise power, especially the low frequency noise level, like Auto-Zeroing, Correlated Double Sampling (one type of Auto-Zeroing technique), Chopper Stabilization [3].

2.1 Auto-Zeroing

The basic principle of Auto-Zeroing is sampling the DC offset and low frequency noise, storing them onto some devices (usually capacitors), and then subtract them off from the noisy signal. Clock and capacitors are two necessary elements of auto zero circuits, so AZ structure is usually applied in switch-capacitor circuits [4].

There are several structures to realize the subtraction of DC offset and low frequency noise. One is subtracting the unwanted noise at the output of amplifiers, shown in Fig. 2.

In this structure, there are four switches named S1 ~ S4. In the DC cancelling clock phase, all these switches are turn on, the offset of amplifier V_{os} is stored on the capacitor C0/C1 by an amount of $A_V V_{os}$, the outputs of AZ circuit named OUT1 and OUT2 remain zero, so in the top view, this amplifier does not have any offset.

But the above structure could be used in only low DC gain amplifier. In CMOS process, the DC offset is usually 1 ~ 10 mV, determined by the size of MOS device and layout pattern. Assuming the DC gain of amplifier to be 60 dB, then the amplified offset which is stored on capacitors could be 1 ~ 10 V, this voltage may be even

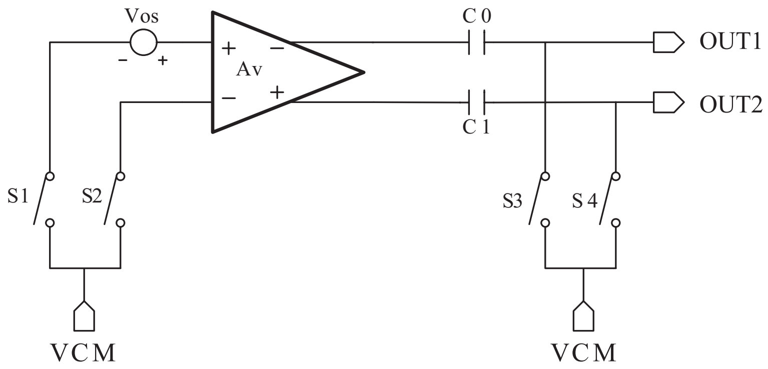
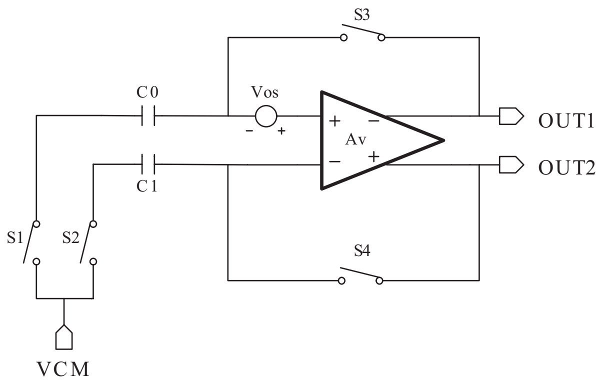


Fig. 2 Output-side DC cancellation

Fig. 3 Input-side DC cancellation



larger than source power. Lots of operational amplifiers have a DC gain higher than 60 dB for better performance, so another structure is needed for this high gain amplifier.

One way to solve this problem is moving the capacitors to the front side of amplifier, like the way shown in Fig. 3.

In the sampling phase, four switches are turned on, the voltage of V_{os} will be stored on C0 without amplification by a factor of A_v, avoiding saturation with large amplitude.

The two structures described above both have capacitors in their signal path, causing limited usage at both switch capacitor circuits and successive time circuits.

In order to avoiding the capacitor in signal path, an auxiliary amplifier is introduced in to make another cancellation path, and then put the capacitors in that path, shown in Fig. 4.

In this structure, the capacitors are placed at the input of auxiliary amplifier, the input voltage is V1, when

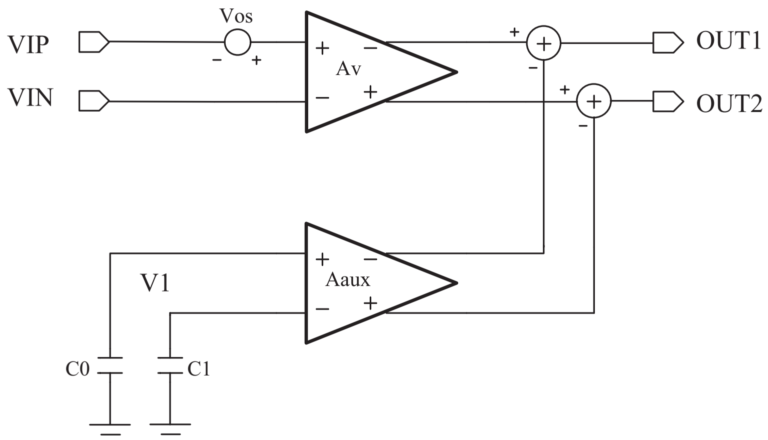


Fig. 4 DC cancellation with auxiliary amplifier

$$V1 = -\frac{A_v}{A_{aux}} V_{os} \tag{5}$$

The offset voltage of the main amplifier is cancelled by auxiliary amplifier perfectly.

2.2 *Chopper Stabilization*

Unlike Auto-Zeroing structure, chopper stabilization does not cancel the offset and low frequency noise by sampling and subtraction, but moving them or signal away from their original frequency to a higher place by modulation, and demodulating them to move back after finishing amplification. So the principle of chopper stabilization is separating the wanted signal and unwanted noise at spectrum level, then the separated noise can be filtered out by following low pass filter.

A clock is required in the chopper stabilization amplifier just like auto-zeroing, but capacitors are not needed, instead of resistors. This makes chopper stabilization more suitable in successive time application.

There are also several structures to realize chopper stabilization amplification. One common way is shown in Fig. 5 [5].

It's composed of eight switches, four resistors and one operational amplifier. The four switches at the front side of amplifier play a role of modulation of signal. The chopping clock has two phase named Φ1,Φ2, switches S1/S4 are controlled by phase Φ1 and S2/S3 are turned on by Φ2. The other four switches act as demodulation, S5/S8 are controlled by Φ1 and S6/S7 turned on by Φ2. Resistors together with operational amplifier amplify the modulated signal by a factor of R2/R1. The process of how chopper stabilization works in spectrum view could be shown as Fig. 6.

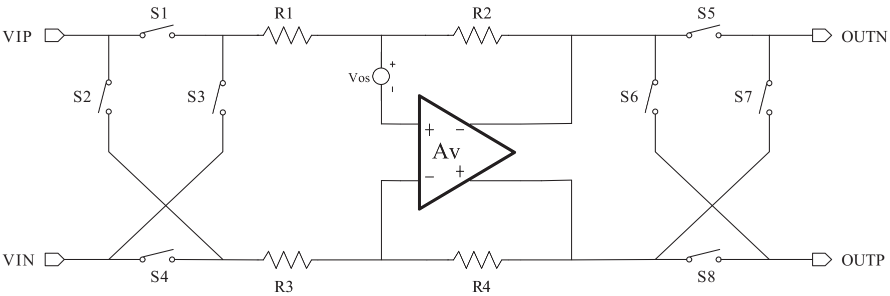


Fig. 5 Chopper-stabilization amplifier

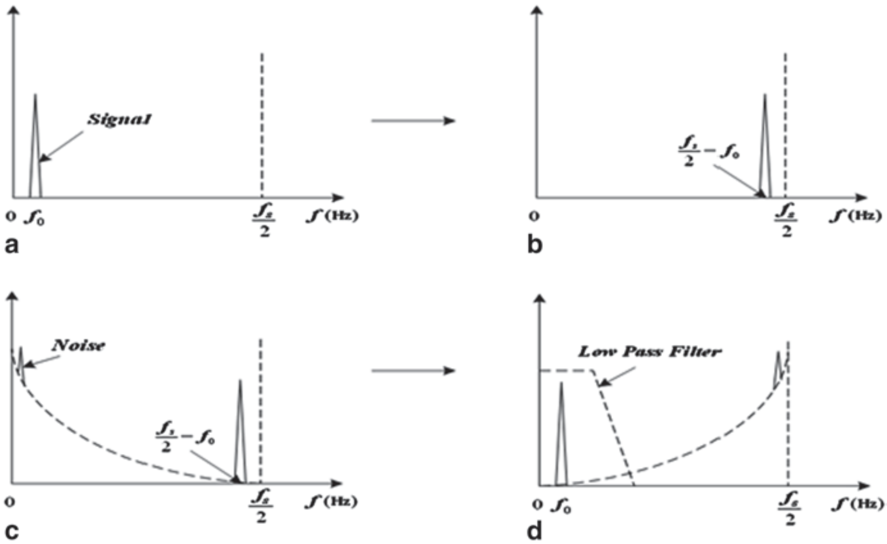


Fig. 6 Spectrum view of chopper-stabilization amplifier

Figure 6a shows the spectrum of input signal, it should be filtered by a low pass filter to wipe off high frequency noise or tones, or else they will be sampled down to low frequency by chopping clock. Figure 6b shows the modulated signal spectrum by the four switches at the input side. Assuming the chopping clock frequency to be f_c, then the signal band is moved to the place at $f_c - f_c$, where f_0 is the signal frequency. Usually f_c is set to be half of the ADC sampling frequency to avoid modulated tones sampled down to signal band, which is assumed to be f_s, so the modulated signal is located at $\mathrm{f}_s/2 - f_0$. The modulated signal is then amplified by the closed loop amplifier by a factor of R2/R1, with all the noise source joined in, like resistor thermal noise, transistor thermal noise, and the most significant flicker noise, shown in Fig. 6c. But fortunately, the signal is placed far away from the low frequency noise. Then the noisy signal is demodulated by the same clock to move

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