Design and implementation of a low-pass filter for microsensor signal processing*

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Abstract: A novel low-pass filter that consists of a switched capacitor filter (SCF) and its antialiasing prefilter and smoothing postfilter is proposed for a microsensor signal processing system, which is used in separation point detection on the surface of micro air vehicles. In the system, the filter is not only applied to finish the function of filtering but also used as the front end antialiasing filter of the over sampling analog-to-digital converter. This proposed implementation mostly relies on the design of a high-precision SCF employing a correlated double sampling technique and optimisation switches. Simultaneously, the multiple-loop feedback low pass filter with good high frequency attenuation characteristics is applied as the pre- and postfilter. The design is implemented in the Central Semiconductor Manufacturing Corporation (CSMC) 0.5 μm double-poly three-metal (2P3M) 3.3 V CMOS technology, with satisfactory results. The chip die area occupies only 0.39 mm^2 and dissipates1.53 mW.

Key words: filter; low-pass; low-power; microsensor signal processing system
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1. Introduction

According to research at the University of California in Los Angeles[1], the detection of boundary layer separation on the surface of a delta wing is of great interest for micro air vehicle (MAV) design and application. The MEMS-based microsensor is the only realistic way to detect the boundary layer separation in real time due to the potential ability of MEMS devices to perform complex functions in a smaller area. There is also the prospect to develop devices that can (1) be easily manufactured, (2) offer low power consumption, and (3) reduce waste[2]. Then the new advancements of microelectronics (real-time signal processing system) have to occur to fully appreciate and test these MEMS devices.

A filter is one of the key blocks in the modern signal processing system. The low-power low-pass analog filter presented here is designed and implemented for the microsensor signal processing system with a power supply of 3.3 V, which is used in separation point detection on the surface of MAVs. It employed a switched capacitor filter (SCF) with its antialiasing prefilter and smoothing postfilter on the same chip. The correlated double sampling (CDS) technique and optimisation switches were applied in the SCF to decrease the nonidealities of switches and operational amplifiers (op-amps). A two order multiple-loop feedback low pass filter was adopted as the pre- and postfilter because it is beneficial to finish the function of filtering and improve the high frequency attenuation characteristic of the whole filter.

2. Filter design

The goal of the analog low-pass filter in the microsensor signal processing system for boundary layer separation detection is to restrict the noise and interference, so that the signal discrimination can be enhanced. Another role of the filter is as the front end antialiasing filter of over sampling analog-to-digital converter (ADC) in the system. According to the research on boundary layer separation, the frequency of the wake near an oscillating cylinder is less than 1 kHz[3]. So the cutoff frequency of the low pass filter should be less than 1 kHz. The filter must have a small direct current (DC) gain variation in order to not influence the detected signal. And the stopband attenuation should be as large as possible at high frequency to ensure that the signal to noise ratio (SNR) of the latter over sampling ADC can be above 80 dB. In addition, the signal processing system will be installed on the surface of the MAV's wings, thus a low power and small chip area would be ideal.

At present, the candidates for application as an analog filter are metallic oxide semiconductor field effect transistors (MOSFET) analog filters and SCFs. The MOSFET analog filter has an accuracy of about 5%. But the accuracy of an SCF integrated on a chip can be determined by the relative capacitance ratio, which is approximately 0.1%. This has proved very attractive for audio applications and data acquisition aspects recently. Therefore a low pass filter (shown in Fig. 1) with a cutoff frequency of 0.7 kHz was proposed based on the Butterworth type with a small ripple in the passband, in which the SCF is the most important part. However, for the sampled-data filter, prefilters and postfilters are needed in SCFs to eliminate the undesired signals located beyond half of the sampling clock frequency and to reconstruct the continuous-time signals.

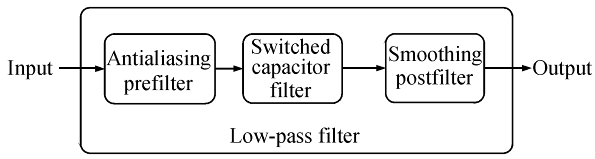

Fig. 1. Proposed low-pass filter framework.

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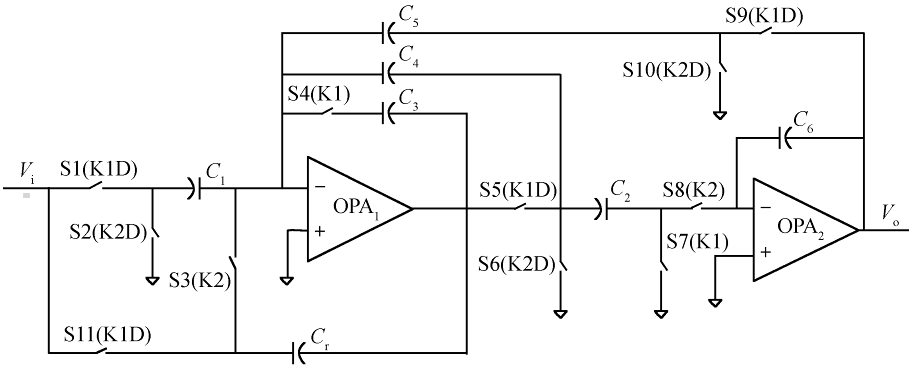

Fig. 2. Switched capacitor filter.

So the two order multiple-loop feedback low pass filter was adopted as the pre- and postfilter in the design, owing to its advantages, including a component-insensitive, low distortion and good high frequency attenuation characteristic. In addition, the response of the overall filter depends upon M, which is the oversampling ratio of the sampling frequency to the cut-off frequency. That is, if M is much greater than 1, the overall response would be closer to the baseband response of the SCF. Otherwise, both the pre- and postfilter responses should be taken into account. The orders of pre- and postfilter transfer functions are determined by the value of M. The higher the orders, the more stopband attenuation is in the overall response. So the sampling frequency of the SCF was presumed to be 128 kHz.

2.1. Op-amp design

The op-amp is the most important active device of the overall filter. The effect of the op-amp performance on the overall filter is considerable. An open-loop DC gain, bandwidth, other parameters meet the design requirements, and low-power, simple structure op-amp should be designed. The conventional two-stage op-amp with approximate 95.76 dB DC gain, 28.35 MHz unity-gain bandwidth (UGBW), 65.94° phase margin and 0.376 mW power consumption when the load is 5 pF (from simulation) was used in the filter. In addition, PMOS transistors were selected to be the input differential stage of the op-amp to inhibit the impact of the drift, noise or other factors of instability.

2.2. SCF design

As shown in Fig. 2, the SCF was implemented based on a biquad filter with a CDS technique to obtain high-precision, low-power and low-complexity in the design.

The transfer function of the biquad filter can be written as

$$H(s) = -\frac{H_o w_o^2}{s^2 + \dfrac{w_o}{Q} + w_o^2}, \tag{1}$$

where

$$H_o = \frac{C_1}{C_5}, \tag{2}$$

$$w_o^2 = \frac{f_c^2 C_2 C_5}{C_3 C_6}, \tag{3}$$

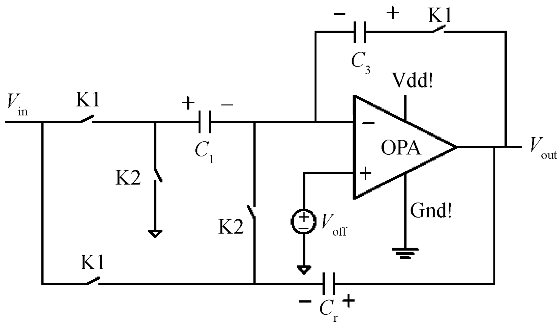

Fig. 3. Offset-free inverting SC integrator.

$$\frac{w_o}{Q} = \frac{f_c C_4}{C_3}. \tag{4}$$

When Q is 0.707, the capacitors' values are $C_1 = C_2 = C_5$ = 500 fF, $C_3 = C_6$, the gain, cutoff frequency and quality factors Q of SCF are determined respectively by the ratio of capacitors C_1/C_5, C_3/C_1, C_4/C_3. And the C_r is a compensation capacitor, with $C_r = C_1$.

Compared with other active filters, the SCF has higher precision. But they are still bothered by the nonidealities of switches and op-amps. So the CDS technique and optimization switches were adopted to obtain higher precision.

The CDS technique can be described as a generalization of the autozeroing technique. It is widely used in sampled-data systems and particularly in SC circuits to build precision blocks[4]. In the SCF, the op-amp is used to create a perfect virtual ground and ensure a lossless charge transfer primitively. But, in fact, the input-referred offset voltage (V_{off}) of the op-amp is inevitable with the ranges typically from 5 to 20 mV in a CMOS technology[5], which becomes more pronounced in low-voltage applications, where the inherent signal swing is reduced.

A kind of CDS technique (offset-free inverting integrator[6]), as shown in Fig. 3, was used in the SCF. Its output voltage changes only by a small amount during the compensation phase. So it does not require such a high slew rate (SR) from the op-amp and has the low gain sensitivity property as well as a very small phase error, which is approximately 0.006°[6, 7]. In the structure, K1 and K2 are non-overlapping clocks. Physically, C_r enables C_3 to discharge to $-V_{off}$ when K2 is high. When K1 is high, C_3 is charged to $V_{in} - (-V_{off})$, the net input

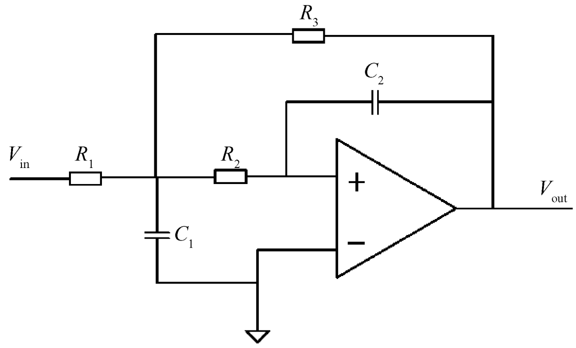

Fig. 4. Two order multiple-loop feedback filter.

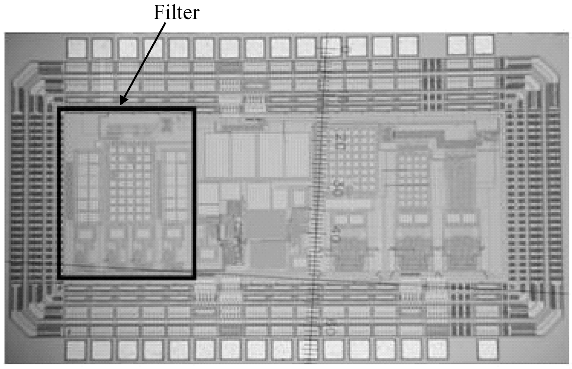

Fig. 5. Microsensor signal processing system chip photomicrograph.

voltage is $(V_{in} + V_{off}) - V_{off} = V_{in}$. So an offset-free integrator is performed. In addition, in the application of the offset-free integrator, the switch beneath capacitor C_3 should move to the other side of C_3, as S4 shown in Fig. 2. The reason is that the V_{gs} of the switch does not easily exceed the oxide breakdown voltage when K1 is high in this instance. Of course, the transfer function of the integrator would not be ruined by the change.

Switch nonidealities can be described in terms of nonlinear switch on-resistance and charge injection[3] (or clock feedthrough). In SCF, the switch is an important component, which works by moving charges into and out of the capacitors. Non-overlapping clocks[4] were used to control the switches, so that not all switches were opened simultaneously and the errors related to input signal would be decreased. In addition, the optimized switch combinations were adopted. That is, the CMOS transmission gate[3] was used in the signal path, namely, S1, S5, S9 and S11. This is a better candidate than both NMOS and PMOS transistors in terms of reducing the input dependent switch on-resistance and the charge injection. S8 in Fig. 2 was realized by using a dummy switch to compensate the charge injection. The dummy switch was connected to the negative input terminal of the op-amp, so it would compensate the charge injected into C_6 from the real switch of S8. Other switches were realized by small dimension NMOS transistors in order to simplify the design, decrease the area as well as lower nonidealities.

2.3. Pre-and postfilter design

The two order multiple-loop feedback low pass filter (shown in Fig. 4) was adopted as the pre- and postfilter, because it yields a larger stopband attenuation than other traditional filters and has a number of advantages, such as a component-insensitive and low distortion.

3. Measurement

The low-power low pass filter was fabricated using Central Semiconductor Manufacturing Corporation (CSMC) double-poly three-metal (2P3M) 0.5 μm 3.3 V CMOS technology. The whole chip occupies 0.39 mm^2. The power consumption is only 1.53 mW. Figure 5 shows a chip photomicrograph of a micro-sensor signal processing system, which is composed of the filter.

Figure 6 shows the measurement wave of the filter. The measured frequency response of the filter is shown in Fig. 7.

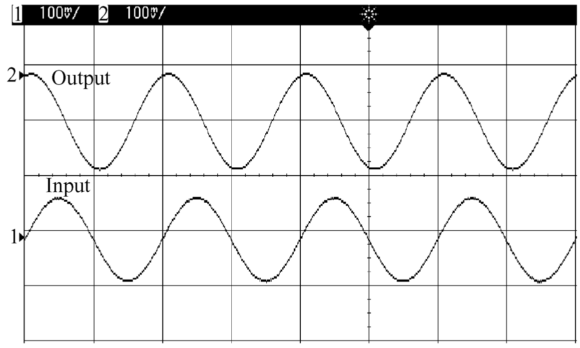

Fig. 6. Measured filter wave.

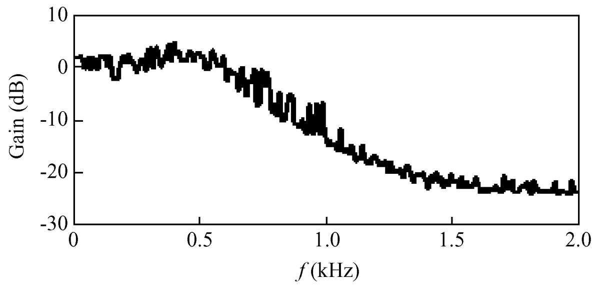

Fig. 7. Measured filter frequency response.

The inband gain is about 0 dB. The cutoff frequency is about 0.7 kHz, and its accuracy is less than 1%.

Because of the measured condition, the stopband attenuation of the filter cannot be tested. But the SNR of over sampling ADC, which is used in the microsensor signal processing system, has been tested to be enough. So the conclusion can be obtained that the stopband attenuation of the low pass filter satisfies the design requirements.

4. Conclusion

A novel low-power low pass filter which fulfills requirements for a micro-sensor signal processing system applied to separation point detection on the surface of a MAV has been proposed. The filter combines an SCF with its pre- and postfilter. The design method, frequency characteristics, and the feasibility of the filter are presented. Firstly, an op-amp with sufficient basic performance and low-power, simple structure was designed to reduce the power consumption and chip area of the filter. Secondly, the CDS technique and optimization switches were proposed in the SCF in order to decrease the nonideal effects and increase the precision of the filter. Thirdly, the two order multiple-loop feedback low pass filter was adopted as a pre- and postfilter to eliminate the distortion the filter and ensure a good high frequency attenuation characteristic. The measurement results show that these methods are especially well suited to the design of a low pass filter, which is feasible and effective for micro-sensor signal processing system applications.

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