A Micro-Watt Second Order Filter for a Chopper Stabilized MEMS Pressure Sensor Interface

Arup K. George, Wai Pan Chan, Zhi Hui Kong, Minkyu Je

Abstract—This paper describes a low-power second-order filter for a continuous-time chopper stabilized capacitive sensor interface, integrated with a fully differential post-CMOS surface-micro-machined MEMS pressure sensor. The circuit uses a single-ended folded-cascode operational amplifier and two GM-C filters connected in cascade. The circuit is realized in a 0.18 μm CMOS process and offers differential to single-ended conversion. The novelty of the scheme is the cascade of two GM-C filters to achieve a second-order filter while minimizing power dissipation. The simulated filter cut-off frequency is 1.14 kHz at common-mode voltage 1.65 V, operating from a 3.3 V supply while dissipating 172μW of power. The filter achieves an operating range of 1V for an output load of 1MOhm and 10pF.

Keywords—Chopper Stabilization, MEMS, Pressure Sensors, Low Pass Filter

I. INTRODUCTION

MEMS capacitive pressure sensors are pervasive in biomedical applications due to the compatibility of MEMS with CMOS processes and its low-cost feature. In addition, the low temperature coefficient, noise and power dissipation make MEMS capacitive sensors ideally suited for battery-operated applications. In this current application, a fully-differential intracranial pressure (ICP) sensor, forming an integral part of an implantable neuro-monitoring system, is developed by post-CMOS surface micro-machining (SμM). Low frequency variation of ICP is a key indicator determining the outcome of a patient subject to traumatic brain injury [1].Key challenges for such circuits are the high impedance sensing nodes, their susceptibility to parasitics, charge leakage and electromagnetic interference (EMI), making it difficult to establish a stable DC bias for the readout stage [2]. A typical SμM MEMS sensor has sensing capacitances less than 100fF. The low sensing capacitances along with low drive voltages limit the signal excursions at the sensing nodes, demanding a very low noise floor for the interface circuit. Raised circuit noise floor limits the minimum possible resolution of the system. SμM sensors' sensitivity is just of the order of atto-farads per mmHg and hence interface has to be very low-noise. Continuous-time voltage (CTV) amplifiers have the lowest noise floor and hence chosen for this implementation [3].

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CTV amplifier with chopper stabilization (CHS) is a common approach for reducing the *1/f* noise and DC offset in capacitive sensing. Chopper amplifiers modulate the input signal above the *1/f* noise corner, amplify the modulated signal and demodulate it back.

Modulation transposes the input signal spectrum around the odd harmonics of the chopping frequency (*fchop*). The input signal has to be band-limited to fchop/2 to avoid aliasing effects after modulation. The modulated signal added with noise and offset gets amplified. The amplifier output is then demodulated. Demodulation transposes the noise and offset to the odd-harmonics of fchop, while restoring the input signal spectrum. This makes the amplifier output devoid of *1/f* noise as well as offset.

However, the finite bandwidth of a practical amplifier introduces some even harmonic spectral components of the chopping frequency to the demodulated signal. Consequently, a low-pass filter becomes necessary to filter out those components and recover the baseband. The filter also removes the output ripples due to the modulated DC offset [4]. In this paper, we describe the design of a differential to single ended low-pass filter with a cut-off frequency of 1 kHz for a CMOS chopper stabilized continuous time voltage amplifier, operating at fchop of 125 kHz.

This filter forms the final stage of a high-gain continuous-time chopper stabilized capacitive sensor interface used for measuring the ICP. GM-C filters are suited for on-chip low pass filter realization, as a large R and C are not required and a lower bias current can give rise to a lower trans-conductance and hence a lower cut-off frequency at a lower power[6].

II. THEORY OF OPERATION

Figure 1 shows the functional block diagram of the capacitive sensor interface. The circuit consists of a fully differential capacitive bridge, a capacitance to voltage converter, de-modulator and a low-pass filter. The system resolution is 1 mmHg over 100 mmHg dynamic range at a bandwidth of 1 kHz.

The low-pass filter that forms the current design is shown shaded. The bridge drive voltage VDRIVE, is controlled by two non-overlapping clocks, φ and φ'. CUP increases, while CDOWN decreases from the nominal value by ΔC, for a change in pressure.

The deviation from the nominal values causes a bridge imbalance and ensuing integration of charge on capacitor CF. VOUT is related to the instantaneous pressure P, nominal pressure, P0 and variations in full range capacitance and pressure as:
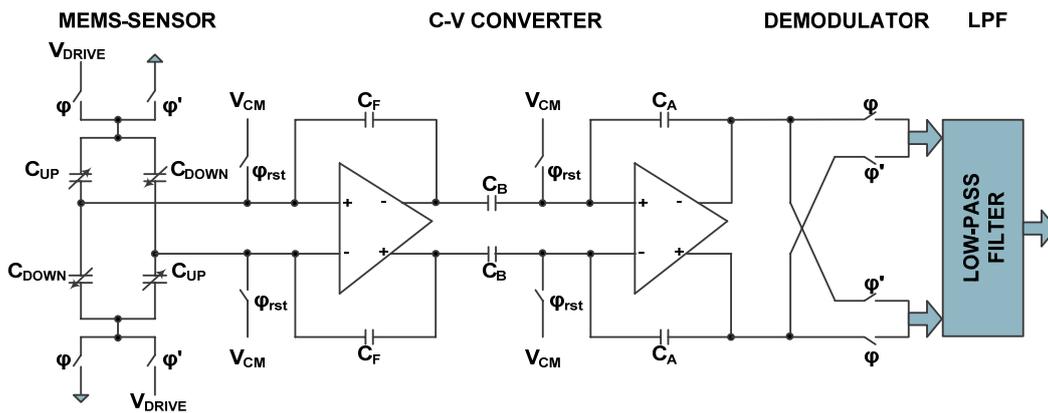
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Fig. 1 Continuous Time Chopper Stabilized C-V Converter
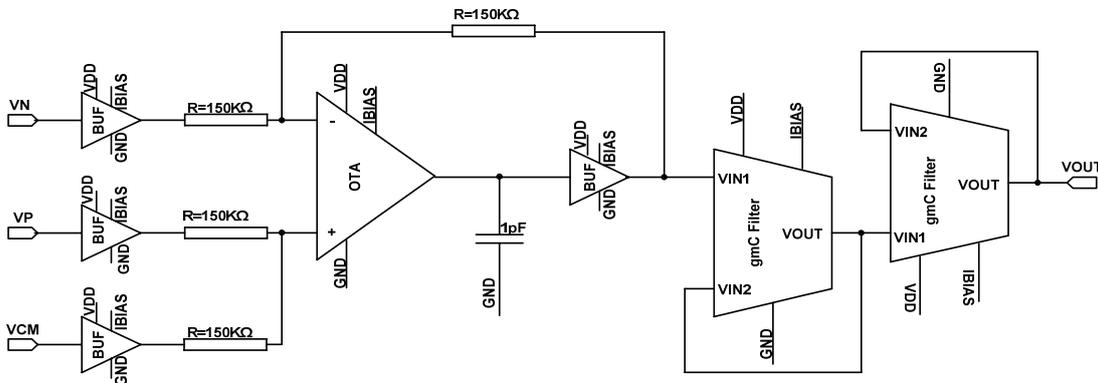

Fig. 2 Low-Pass Filter forming the final stage of the C-V Converter

$$V_{OUT} = \left(\frac{C_B}{C_A} \right) \left(\frac{(P - P0).\Delta C_{full\_range}}{\Delta P_{full\_range}.C_F} \right) (V_{DRIVE} - V_{CM}) \quad (1)$$

The bandwidth requirement of the system is dictated by the maximum frequency of interest in the intracranial pressure [1]. For our proposed design, the system bandwidth is fixed as 1 kHz to capture the low-frequency variation of ICP. Hence the cut-off frequency needed for the filter is also 1 kHz. The filter has to have sufficiently high roll-off to ensure sufficient attenuation after *fchop*. To ensure a good compromise between the required roll-off rate and number of filter stages, a second order filter is chosen. The aim is that there is at least 40 dB attenuation at *fchop/2*. The filter has to generate a single ended output from the differential input of the gain stage op-amp. Being an implantable system, the filter should only dissipate micro-watt power to prolong battery-life.

III. CIRCUIT IMPLEMENTATION

Figure 2 shows the second-order low-pass filter that forms the final stage of the sensor interface. A differential amplifier takes the difference of the input voltages from the de-modulator and adds the common mode voltage. The inputs as well as the outputs are buffered to avoid loading effects. The output is fed to a cascade of two PMOS input GM-C filters, each connected in negative feedback.

PMOS input stages are used to lower the flicker noise. A folded cascode op-amp designed for 80dB open-loop gain, gain bandwidth of 1MHz and self-compensated by a 10pF load at 5μA bias current is used as differential amplifier. Buffers are realized using a differential pair in unity feedback. Figure 3 shows the schematic of the GM-C filter [6]. The transistors M3 and M4 operate in the triode region. M3 and M4 undergo varying bias conditions dependent on the input. The bias current is 2.5μA. The filter cut-off frequency is inversely proportional to the input bias current as well as the trans-conductance of the triode transistors. The output is buffered and the circuit is connected in negative feedback to increase the input common mode range. Buffer circuits are used for coupling the input voltages to the differential amplifier as well as at the input of the GM-C filter. Figure 4 shows the layout design of the proposed filter based on a 2P5M 0.18 μm CMOS technology from Global Foundries. MIM capacitors are used in the GM-C filter. Poly resistors are used for feedback resistors, as they provide high resistance while consuming smaller area.

IV. RESULTS AND CONCLUSION

The filter is designed to operate at a common mode input voltage of 1.65 V. Figure 5 shows the filter bandwidth as a function of the input voltage across various process corners.

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At 1.65 V common-mode input, the filter has a 3-dB frequency of 1.14 kHz at the typical corner. The filter cut-off frequency increases as the common mode voltage approaches 2.5 V giving a linear range of 1 V. The cut-off frequency increases for the fast corner due to the increased bias-current. A summary of the simulated parameters of the filter are shown in Table I. The filter is taped out using Global Foundry 0.18 μm CMOS process. The filter achieves the desired cut-off frequency over a good range of input voltage while dissipating micro-watt power.
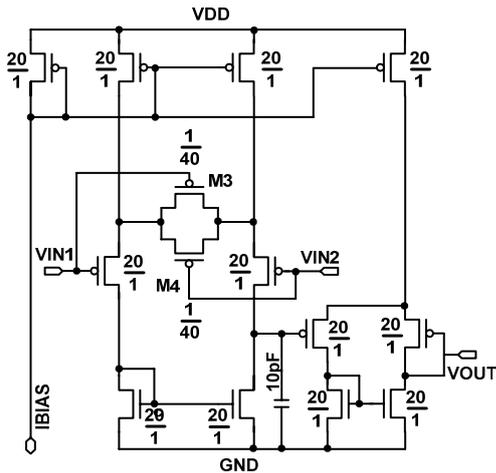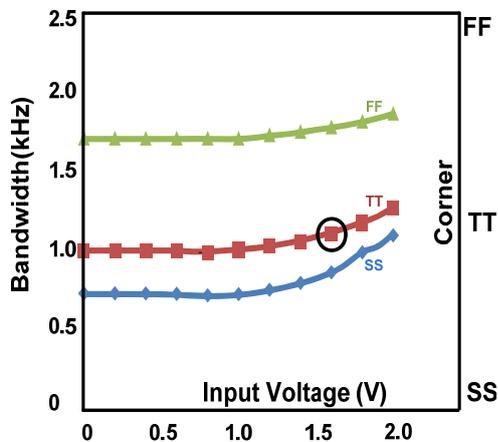
Fig. 3 GM-C Filter

Fig. 4 Layout of the Low-Pass Filter

Fig. 5 Filter Bandwidth across Corners

TABLE I
FILTER PARAMETERS

Parameter	Value
process	0.18μm, 2P5M
power	172μW
bandwidth	1.14kHz
input range	1V-2V
output load	1M//10pF

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