Time-encoded audio MEMS sensors optimized for edge computing

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***Abstract*—Conventional read-out electronics for MEMS capacitive microphones require biasing circuitry, consisting of charge pump and high-ohmic link between the ASIC and the MEMS. Biasing circuitry influences the sensitivity and the attainable SNR. On the lookout for new solutions which simplify the circuit scalability, it is of interest to envisage architectures that do not require the microphone biasing and the sensitivity depends on other parameters. Time-encoding architectures allow to directly convert a capacitance signal into a frequency one by means of capacitance-controlled oscillators. In order to boost the sensitivity and the achievable SNR, we propose the cross-connected configuration rather than grounded sensors. Although this technique does not lead to high quality microphones, this work is intended for Human-Machine Interface applications given their moderate SNR requirements and the need for low cost, area and power.**

***Index Terms*—ADC, MEMS microphone, HMI, time-encoding**

I. Background and Motivation

Capacitive MEMS sensors are widely used in Human-to-Machine Interface (HMI) applications (e.g. wearable electronics). A conventional read-out for the MEMS sensor is based on a capacitance-to-voltage conversion by keeping constant the charge stored on the plates of the MEMS capacitor [1]. The constant-charge read-out is sufficiently sensitive if the sensor is biased by a large dc voltage (obtained by means of a charge pump); also, to avoid charge leakage, the sensor is connected to a high-ohmic bias resistor. The need for large bias voltage and resistor hinders scaling; moreover, the high impedance node, directly connected to the sensor, is subject to interference [2]. All these reasons ignite the interest in innovative techniques to read the sensor, which should be optimized to targeted applications and avoid the usage of the charge pump. The main constraints are power consumption, cost and available area, instead of high-quality audio acquisition and SNR performance.

II. MEMS Capacitance Controlled Oscillators

Time-encoding techniques have proved to be suitable to implement Sigma-Delta ADCs to digitize the signal detected by the microphone by means of VCOs and digital electronics.

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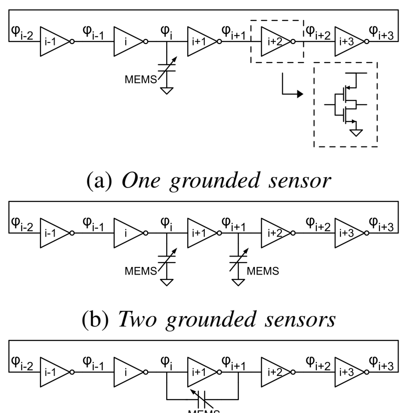

(a) *One grounded sensor*

(b) *Two grounded sensors*

(c) *Cross-connected sensor*

Fig. 1: Different configurations of MCCO.

The main advantages are the scalability and the digital nature of time-encoded signals. Mainly, VCO-based ADCs need a voltage-encoded input, which is obtained as described in part I. In absence of biasing circuitry, a direct capacitance-to-frequency conversion may be achieved by modulating the oscillation frequency of a ring oscillator (RO) with the MEMS capacitor. Thus, this paper deals with MEMS capacitance controlled oscillator (MCCO). The easiest way to connect the sensor to the RO is the grounded configuration, which is shown in Fig. 1(a). This solution is simple but the sensitivity of the capacitance-to-frequency conversion is not enough to compensate the small capacitive signal. As a consequence, for reasonable values of the oscillation frequency and the sampling frequency (which are related to the power consumption), the resulting performance of the ADC in terms of SNR is low. An inefficient way to increase the sensitivity is to use more sensors (cf. Fig. 1(b)). Our proposal is referred to as cross-connected configuration, shown in Fig. 1(c)) to boost the performance of the read-out by using just one sensor. The sensor is connected across one of the CMOS inverters of the RO. In Fig. 2, the sensitivity of the Grounded Sensor (GS) configuration with one or two sensors is compared to the Cross-Connected Sensor (CCS) case. The latter provides more sensitivity than using two sensors.

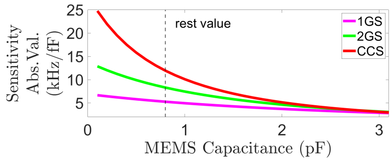

Fig. 2: Modulus of sensitivity against MEMS capacitance.

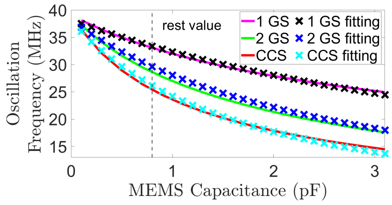

Fig. 3: Simulation results fitted by analytical formulae.

III. Analytical Study and Design Example

The improvement in sensitivity comes from a time-dependent Miller effect, which intuitively increases the number of effective sensors connected to the RO. It can be shown that the oscillation frequency f_{osc} and the sensitivity k_{MCCO} of the RO can be expressed as:

$$f_{\mathrm{osc}} = \frac{I}{V_{\mathrm{DD}}(C'_{\mathrm{OX}}WLN + \beta\, C_{\mathrm{MEMS}})} \tag{1}$$

$$k_{\mathrm{MCCO}} = \frac{\partial f_{\mathrm{osc}}}{\partial\, C_{\mathrm{MEMS}}} = \frac{-\beta\, I}{V_{\mathrm{DD}}(C'_{\mathrm{OX}}WLN + \beta\, C_{\mathrm{MEMS}})^2} \tag{2}$$

where V_{DD} is the supply voltage, C'_{OX} is the gate capacitance per unit area, W and L are the gate width and length, N is the number of CMOS inverters and current I can be approximated as $I = \frac{\mu C_{\mathrm{OX}}'}{2}\frac{W}{L}(V_{\mathrm{DD}} - V_{\mathrm{T}})^2$ [3]. The parameter β allows a general usage of these equations in all the case studies; basically, it represents the number of grounded sensors. After fitting it turns out that CCS can be approximately studied as an effective number β of grounded sensors which is more than one (e.g. β is around three in the case depicted in Fig. 3). Also, Fig. 3 demonstrates that the analytical model is in accordance with the results of transistor-level simulations in a 130nm technology node. The increase in sensitivity is not excessively high, but it is remarkable that the price paid is just a slight increase in power consumption. At the same time, no bias voltage and bias resistor have been required (and the related problems are avoided). The time-encoded output of the MCCO is processed by digital electronics to achieve a complete first-order Sigma-Delta ADC as shown in Fig. 4 [4]. The main trade-off is between power and SNR performance; evidently, an increase in power consumption improves the SNR of the ADC, but at the same, as already stated, it is also one of the main constraints for wearable electronics applications. As a design example, let us assume the sensor sensitivity as $9\,\mathrm{fF/Pa}$ at $1\,\mathrm{kHz}$, the rest value of the MEMS capacitor equal to $0.8\,\mathrm{pF}$, V_{DD} equal to $1V$ and a five-stage RO in a 130nm CMOS technology node with the following transistor sizes: $L_{\mathrm{n}} = L_{\mathrm{p}} = 2\,\mu\mathrm{m}$, $W_{\mathrm{n}} = 15\,\mu\mathrm{m}$ and $W_{\mathrm{p}} = 30\,\mu\mathrm{m}$. Sampling frequency is chosen as $f_{\mathrm{s}} = 2.75\,\mathrm{MHz}$ and analog bandwidth as $ABW = 6.8\,\mathrm{kHz}$. Figure 5 shows the amplitude spectrum of the digital output of the ADC in Fig. 4 given a sinusoidal input of $94\,\mathrm{dB}$ SPL at $1\,\mathrm{kHz}$. The SQNR estimate in the ABW is 58.9 dB. Instead, the SNR estimate due to phase noise can be computed by referring it to the input, as explained in [5]; the A-weighted SNR computation due to phase noise is approximately $55\,\mathrm{dBA}$. It is noteworthy that the current consumption of the simulated MCCO is around $83\,\mu\mathrm{A}$.

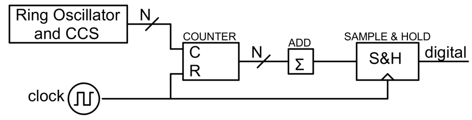

Fig. 4: First-order noise shaped Sigma-Delta ADC.

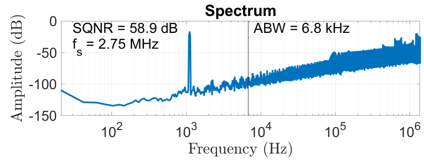

Fig. 5: Amplitude spectrum of a digitized sinewave.

IV. Conclusion

This manuscript proves that proposed CCS configuration provides more sensitivity than GS one. Although the boost has been achieved, the SNR computation is moderate ($\geq 50\,\mathrm{dB}$). Nevertheless, targeted HMI application do not require high quality microphones. It is noteworthy that CCS architecture does not require biasing circuitry for the MEMS sensor. The architecture is prone to be scaled. The average power consumption of the MCCO is $83\,\mu\mathrm{W}$ and the improvement of the SNR performance can be obtained at the price of an increase in power consumption.

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