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Research Article

A High Accuracy Capacitance-to-Digital Converter with Improving Nonidealities Effects

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Abstract

This paper presents a high-precision capacitance-to-digital converter (CDC) based on period-modulation (PM) for grounded capacitive sensors. In this work, with a symmetrical design, the performance of the proposed capacitance to digital converter is significantly improved by applying zoom-in and three signal auto-calibration techniques. The dominant nonidealities of the CDC circuit are located at the three asymmetrical phases of the auto-calibration pathes. These effects are investigated here, mainly caused by charge injection of switches and associated parasitic effects. These nonidealities are reduced by utilizing dummy switches at asymmetrical paths of the applied auto-calibration. The proposed interface is designed as an integrated circuit using a standard 0.18µm CMOS technology. A worst-case capacitance error less than 0.2fF for a 10pF sensor capacitor with maximum variation of 200fF, and parasitic capacitance of up to 20pF is obtained. The CDC achieves an absolute capacitance resolution of 0.479fF across a 10pF sensor capacitance with a 200fF variation, corresponding to an energy efficiency of 6.94pJ/step. The achieved latency is 128µs and the CDC consumes 170µA from a 2V power supply.

Keywords: Capacitive-to-voltage converter (CVC), Zoom-in technique, Grounded capacitive sensor, Dummy switch.

Highlights

- A novel structure of symmetrical capacitance to digital converter.
- Achieving low noise level and high accuracy.
- Improving non-linear effects using circuit techniques.

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1. Introduction

Capacitive sensors are widely used in high-tech industrial applications because they do not consume static power which makes them attractive for limited energy budget interface circuits [1]. They can be classified as capacitive sensors with active target [1, 2] and grounded target [3–5] electrodes. Interface electronics favor using sensing capacitors with active target electrodes due to high noise immunity and insensitive to the sensor parasitic capacitances. Moreover, the implementation of a fully differential structure to eliminate systematic errors in the interface is complicated for the grounded one. However, in some applications grounded capacitive sensors are preferred [3–5].

Recently, there have been a several solutions in the research related to the capacitive sensors and their associated interface circuits. The sensor capacitance measurement strategy mostly is based on converting the sensor capacitance to digital by using a capacitance-to-digital converter (CDC). This can be done with such configurations as analog-to-digital converter (ADC) [1], period modulation (PM) [4], [6], sigma-delta modulator [5], pulse-width modulation (PWM) [7], etc. In the PM CDCs, the resolution can be traded for conversion time by counting the duration of multiple periods using a digital divider, which makes them quite flexible [6].

A more promising solution for realizing an efficient CDC is utilizing a front-end with a zoom-in structure [2, 8, 9]. It can relax the high dynamic range requirement of the following stage. Auto-calibration is also an attractive technique to eliminate any systematic errors in symmetrical paths of the systems [10]. The interface including auto-calibration also improves the measurement stability, but at the cost of measurement time and also the complexity of the design. It should be noted that the corresponding interface use of a multiplexer (MUX) for selecting sensing elements and asymmetrical paths of the auto-calibration can add some systematic errors to the system and thus require careful design.

In this brief, a high-precision interface circuit based on PM suppressing systematic errors for grounded capacitive sensors is proposed. The effectiveness of error elimination for the proposed interface is achieved with a zoom-in technique and a symmetrical design of the applied auto-calibration.

2. Innovation and contributions

This paper presents a high-precision capacitor-to-digital converter based on period modulation for grounded capacitive sensors. The performance of the interface is significantly improved by the symmetrical design and the use of auto-calibration techniques. Non-ideal circuit effects, mainly caused by charge injection of switches and associated parasitic capacitors, have been reduced by using dummy switches in asymmetric auto-calibration paths.

3. Materials and Methods

The zoom-in CVC includes the sensor parasitic capacitances and the auto-calibration. A feed-forward based-active shielding technique is applied to the first shield of the connection cable to eliminate the parasitic capacitances effect. A MUX is used to select the reference capacitors and the sensor capacitor. When selecting these reference capacitors, their charges will be transferred to the output of the CVC by chopping concept.

Three-signal auto-calibration can reduce unwanted effects such as switches charge injection and parasitic capacitances, in case of the symmetrical path for all inputs. On the other hand, non-symmetrical paths have different parasitic capacitances which in turn lead to error.

4. Results and Discussion

The proposed CDC has been designed and implemented using 0.18μm standard CMOS technology. Results have been verified for a power supply of 2V, and the measured value for the supply current is 170μA. The CVC and the integrator stages employ the recycling folded-cascode amplifier [12], with equal supply currents of 75μA. The feedback and the integration capacitors of the corresponding stages are selected such that the output of the amplifiers does not saturate beyond the maximum input capacitance range. The comparator consists of a simple differential pair followed by a Schmitt trigger. It should be noted that the comparator's propagation delay is eliminated by applied auto-calibration. To investigate the nonidealities caused by switches, both the conventional and the zoom-in CVCs are used as a front-end of the CDC

The absolute accuracy for a conventional and zoom-in CVC along with the calculated absolute accuracy for a conventional one versus the width of the switch (W) are investigated. The simulated results for the conventional CVC are in close agreement with the theoretical analysis. Also, the zoom-in structure can suppress these effects significantly.

To investigate the effect of dummy switches on absolute error of the interface including auto-calibration, the Monte Carlo analysis has been utilized for dummy switches. This investigation is repeated for 100 iterations and the sensor capacitance variation of up to 200fF, the reference capacitors 0pF and 0.5pF, while the sensor parasitic capacitances are 20pF. The average error is almost 0.16fF and its standard deviation is σ=7aF.

Moreover, the absolute error of the zoom-in CDC with and without dummy switches has been investigated, while the sensor variation is changed up to 200fF, and its parasitic capacitances are 10pF and 20pF. In the case of without dummy switches, the capacitance error is about 8fF. However, as expected, it can be seen that this error is significantly reduced by adding the dummy switches, which resulted in an increase in absolute accuracy of more than 5 bits.

The absolute error of the CDC was checked according to the changes of the sensor capacitor and the parasitic capacitors of the cable up to 30pF. This error is less than 0.2fF for cable capacitors below 20 pF, and with the increase of the cable parasitic capacitors, the system accuracy has decreased due to settling error.

The accuracy of the interface was investigated by changing the sensor capacitor and for different gains of the amplifier, while the parasitic capacitors of the cable were 20pF. According to the design target, we need a gain higher than 93 dB to ensure the accuracy to be above 10 bits. As can be seen, the measured error of the sensor capacitor at gains lower than this value has increased.

Furthermore, the accuracy of the interface for different corners has also been investigated by changing the sensor capacitor up to 200fF and the cable parasitic capacitances of 20pF. As can be seen, the absolute error of the proposed zoom-in CDC is almost below 0.2fF for all corners which requires our target design.
In order to estimate the total noise of the CDC, a transient noise simulation was performed for 100 iterations and then the output jitters were measured for three different phases of applied auto-calibration. The standard deviations of the three phases are almost in the same range.
Finally, a summary and comparison of the proposed converter with recent interface circuits is done, which the results are given in table 1. The energy efficiency of these converters has been evaluated by the well-known Figure of Merit (FOM) with the following equations [13-17].

5. Conclusion

A high-precision interface based on period-modulator for grounded capacitive sensors has been proposed. The major nonidealities of the CDC were discussed. It was shown that the effect of such nonidealities of the CDC can be reduced by applying the zoom-in technique and utilizing dummy switches at asymmetrical paths of applied auto-calibration. A worst-case capacitance error less than 0.2fF is achieved for a sensor capacitor with a nominal value of 10pF, variation of only 200fF, and sensor parasitic capacitances of up to 20pF. The achieved latency including chopping and auto-calibration is 128µs. The overall zoom-in CDC demonstrates an absolute capacitance resolution of 0.479fF with an energy efficiency of 6.94pJ/step, while consuming 170µA from a 2V power supply.

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Appendix

Table 1. Performance summary and comparison with state-of-the-art works

Ref.	TCAS 17 [5]	TCAS 18 [13]	TCAS 22 [14]	JSSC 21 [15]	JSSC 22 [16]	ISSC 20 [17]	JSSC 22 [18]	This work
Technology (µm)	0.18	0.18	0.18	0.11	0.04	0.18	0.11	0.18
Type of sensor	Grounded	Active	Active	Active	Active	Floating	Active	Grounded
Power supply (V)	2.6	1.5	0.8 & 1	1.2	0.6 & 1.1	1.8	1.5	2
Sensor range (pF)	10	10 ~ 10000	5.7	0 ~ 3.15	0 ~ 5	0 ~ 10	0.2–1.5 pF	0 ~ 10.2
Abs. cap. res. (fF)	0.06	0.207	0.186@4pF	0.0179@1pF	0.29	0.042	0.0215	0.479
Meas. Time (µs)	3072	128	180	1010	12.5	1000	1200	128
Power cons. (µW)	2340	15	23.2	1.02 ~ 3.19	6.4	563	120	340
ENOB (bits)	17.4	13	13.1	14	12.3	16.07	14.3	12.6
FOM (pJ/step)	41.5	0.234	0.67@4pF	0.094@1pF	0.016	8	7.14	6.94

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