Capacitive Sensor Circuit with Relative Slope-Boost Method Based on a Relaxation Oscillator

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ABSTRACT

This paper presents a relative slope-boosting technique for a capacitive sensor circuit based on a relaxation oscillator. Our technique improves jitter, i.e. resolution, by changing both the voltage slope on the sensing and the reference sides with respect to the sensor capacitance. The sensor prototype circuit is implemented in a 180-nm standard CMOS process and achieves resolution of 710 aF while consuming 12.7 pJ energy every cycle of 13.78 kHz output frequency. The measured power consumption from a 1.2 V DC supply is 430 nW.

KEYWORDS

Capacitive sensor circuit, CMOS, jitter, relaxation oscillator, slope-boost, ultra-low power

1 Introduction

Capacitive sensor circuits can be used for many applications, such as sensing acceleration, pressure and so on [1-3]. The type of capacitive sensors converting the capacitance value to period is called Period Modulation (PM) type. Fig. 1 (a) shows the schematic of the general PM-type capacitive sensor circuit. The PM-type sensor circuit has mainly composed of a relaxation oscillator, generating square wave with periods proportional to the values of resistance and capacitance [4]. As the period of the square wave is counted, the value of capacitance is converted to digital value easily.

The challenge of the PM-type sensor circuits compared to other sensor circuits is low resolution which depends on jitter generated at the relaxation oscillator. Fig. 1 (b) illustrates the process of jitter generation, where V_{noise} is input referred noise of the comparator in the relaxation oscillator. The voltage of minus input terminal at the comparator is $RI + V_{noise}$. Thus, V_{noise} disturbs the timing of logic inversion at reset logic connected at the output of the comparator, and this disturbed timing is called jitter which depends on the voltage slope in this circuit topology [5]. There is a trade-off between the voltage slope and current consumption. Therefore, we need to decrease the jitter to achieve finer resolution while care should be given on keeping the energy consumption low.

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This work proposes jitter reduction technique increasing the voltage slope of input terminal at the comparator, which is explained in the next section. Section 3 focuses on the measurement results. Finally, conclusions are provided in Section 4.

2 Slope-Boost Capacitive Sensing Circuit

Fig. 2 explains the proposed relative slope-boost technique. By comparing V_C and reversed slope V_{Ref} , the voltage slope relatively increases to $Slope_C - Slope_{Ref}$, and jitter can be reduced by 33% in simulation with very small increase in energy consumption.

Fig. 3 illustrates the schematic of the proposed capacitive sensor circuit composed of a differential comparator, a latch, a subtraction circuitry, resistance, and capacitance. When Φ is high, the input voltage at comparator is

$$V_C = V_{dd} \cdot \left\{ 1 - \exp\left(-\frac{1}{RC_m}t\right) \right\}$$

$$V_R = V_{dd} - V_C = V_{dd} \cdot \exp\left(-\frac{1}{RC_m}t\right),$$

where C_m is capacitance of the sensor. When V_R matches V_C , comparator output reverses. The measurement time can be calculated as $RC_m \ln(2)$. When Φ is low, reference time can be calculated as $RC_{ref} \ln(2)$ similarly, where C_{ref} is reference capacitance. Therefore, oscillation period is $R(C_m + C_{ref}) \ln(2)$, and C_m can be measured from oscillation period as R and C_{ref} is known.

3 Measurement Result

Fig. 4 shows the photograph of a test board and a prototype circuit IC fabricated in a 180-nm standard CMOS process. The core area of our circuit is $198\text{-}\mu\text{m} \times 280\text{-}\mu\text{m}$. Fig. 5 shows capacitance vs. period characteristic showing linear behavior. Fig. 6 provides the measurement result at $C_m = 5\text{pF}$. The measured output frequency is 16.8kHz, and resolution is 710aF while consuming 25.7pJ every cycle from a 1.2V power supply. Measured jitter is 4.92ns, and current and power consumptions are 359nA and 430nW. This jitter can be reduced by time averaging. The red dots in Fig. 6 are plotted with number of averaging period (N period) of 0, 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, and 10000; from left to right. The best resolution is obtained at 710aF when N is 50,

4 Conclusions

This paper proposes relative slope-boost technique for reducing the jitter caused by the comparator in the PM-type capacitive sensor circuit. The proposed capacitive sensor circuit achieves low energy consumption and high resolution compared to state-of-the-art capacitive sensor circuits as shown in Table I. As a result, the proposed circuit technique can contribute to longer battery life of IoT devices, with accurate sensor readings.

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Figure 1: (a) Conventional PM-type capacitive sensor circuit based on relaxation oscillator, and (b) output voltage waveform illustrating the cause of jitter.

Figure 2: The proposed relative slope-boost to reduce jitter.

Figure 3: (a) The proposed capacitive sensor circuit based on relaxation oscillator, (b) schematic of the subtraction circuit for reversed slope generation and these parameters.

Figure 4: Test board and the prototype circuit in 180 nm CMOS.

Figure 5: Measured period vs. measured capacitance

Figure 6: Benchmark

Table 1: Comparison

	TRANS 2019	VLSI 2018	ISSCC 2015	This Work
	[1]	[2]	[3]	
Tech [nm CMOS]	180	130	160	180
Type	SAR	PM	PM	PM
Power[μ W]	1.59	8.2	14	0.43*
Input range [pF]	3.6	20	0-8	0-197
MeasTime [μ s]	810	482	210	59.7*
Energy[fJ]	1290	116	2940	25.7
Resolution [aF]	150	2345	1443	710*

* measurement with 5 pF