A Novel Offset Calibration Method to suppress Capacitive Mismatch in MEMS Accelerometer

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An innovative way to cancel out the capacitance mismatch in MEMS accelerometers is presented. The need for the large capacitive arrays or the trimming circuit is eliminated by the use of tuning voltages for offset control. Either broad capacitive matching or smaller resolution can be achieved by reconfiguring offset capacitors and calibration voltage steps. Measured result shows suppression of more than 40 fF capacitive mismatch into 1.16 fF enabling a 10X improvement in the scale factor of an accelerometer as compared to an un-calibrated design.

1. INTRODUCTION

Since its first commercialization in 1990s, the MEMS capacitive accelerometer became an essential component for variety of applications such as automobile and mobile industry given its small form-factor and ability to sense miniscule acceleration. The changing capacitance caused by the movement of the proof-mass under acceleration is converted to an electrical signal through readout circuitry. However, any capacitance mismatch between MEMS electrode caused by the non-ideal nature of the system is also translated to electrical signal as well; which is usually shown as an offset. This is a critical problem when designing accelerometer as it limits the maximum achievable capacitance to voltage gain ($CV_{\text{gain}}$) and result in poor dynamic range as well as high zero-g-offset.

This paper discusses a novel method to cancel out the capacitive mismatch. The section 2 discusses about the cause of the offset and existing techniques to cope with. The section 3 introduces a proposed calibration scheme followed by the measurement result in section 4.

2. CAPACITANCE MISMATCH

2.1. Origin of the problem

Figure 1 shows a schematic of an accelerometer interfaced with switch capacitor (SC) amplifier. The MEMS accelerometer, which is represented as changing capacitor in opposite direction, is consecutively charged and discharged, converting acceleration signal into the voltage following equation (1). This readout scheme, which is called differential sensing, is widely used given its ability to suppress common mode noise and extend the $CV_{\text{gain}}$.

\[
\begin{align*}
0.5VDD(C_{p1} - C_{n1}) &= C_F(V_{\text{cm}} - V_{\text{out}1}) \\
0.5VDD(C_{p2} - C_{n2}) &= C_F(V_{\text{cm}} - V_{\text{out}2}) \\
\therefore \Delta V &= V_{\text{out1}} - V_{\text{out2}} = \frac{0.5VDD}{C_F} \Delta C \\
(\Delta C &= C_{p1} - C_{n1} + C_{p2} - C_{n2})
\]

(1)

The static capacitance, $C_{p1}$, $C_{n1}$, $C_{p2}$, and $C_{n2}$ are designed to be identical and theoretically only the acceleration signal should be shown as an output by the subtraction process in SC-amplifier. However due to process variation during fabrication and the parasitic from the interconnection between sensor and circuit, certain mismatch exists between capacitances. This value is amplified and shows as an offset voltage, modifying the transfer function (1) into (2).

\[
\Delta V_o = \frac{0.5VDD}{C_F} \Delta C_{\text{acceleration}} + \frac{0.5VDD}{C_F} \Delta C_{\text{mismatch}} 
\]

(2)

Minimizing these imbalances in MEMS-level is difficult task as it is completely random and hard to predict. In often cases, the capacitance mismatch (100–500 fF) is comparable or bigger than the changing capacitance caused by the acceleration (10–100 fF/g), creating larger offset than actual signal. Under high $CV_{\text{gain}}$ settings, the output will be rails, limiting the maximum achievable sensitivity. Furthermore as the mismatches are usually temperature dependent, the sensor suffers from the drift under different environmental conditions.

2.2. Existing calibration techniques

Several calibration methods have been reported to solve the mismatch problem. Figure 2(a) shows a trimming block...
to tune the offset into desired level [1]. The authors have achieved combined scale factor of 3.2 V/g from a sensor having capacitive sensitivity of 0.4 fF/g. However, this requires an additional amplifier, which increases the power consumption and the system complexity. Also the tuning range is quite limited so that only small amount of capacitance is calibrated.

Figure 2(b) implements a binary weighted capacitor array to directly cancel out the mismatch [2]-[3]. It has has larger tuning range and sub-fF resolution by connecting series and parallel capacitor. Nevertheless large area is required for the array and the matching network is prone to parasitic due to small capacitive resolution.

Figure 2(c) was introduced to cancel out the offset caused by the bond-wire [4]. The parasitic capacitance is measured and suppressed by modulating the spring constant by electrostatic force inside the ΔΣ control loop. The total offset of 350 mg caused by the wire deformation is suppressed into electrostatic force inside the control loop. The total offset by the bond-wire small parallel tuning range and to directly cancel out the mismatch [2].

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To tune the offset into desired level [1]. The authors have achieved combined scale factor of 3.2 V/g from a sensor having capacitive sensitivity of 0.4 fF/g. However, this requires an additional amplifier, which increases the power consumption and the system complexity. Also the tuning range is quite limited so that only small amount of capacitance is calibrated.

We propose a novel calibration technique that does not suffer from the drawbacks mentioned earlier. The key concept is to use the voltage as a calibration knob to control the amount of charge transferred. Figure 3 shows the schematic of the interface circuit with the calibration block. In charging phase (§1), the MEMS and the offset capacitor is connected to the supply and calibration voltage, storing the charge equivalent to $C_{off}*(VDD-V_{cal})$ and $C_{pi}*(VDD-V_{cmm})$ (for $C_{pi}$ case). During amplification phase (§2), stored charges are transferred to the feedback capacitor and the output voltage is expressed as equation (3). The capacitance mismatch is nulled through tuning the calibration voltage.

$$
\Delta V_{o} = \frac{0.5VDD}{C_f} (\Delta C_{avol} + \Delta C_{c_{rmsv}}) + \frac{C_{off}}{C_f} (0.5VDD - V_{cal})
$$

Compared to the capacitor-array, proposed method has broad feasibility in terms of resolution and trimming. For example, when 1 fF capacitance mismatch needs to be calibrated, required voltage is 2.5 mV using 500 fF offset capacitor. This is a reasonable value, which can be easily done through simple DAC and on-chip capacitor. Whereas in capacitor-array, generating 1 fF resolution is challenging as minimum Metal-Insulator-Metal (MIM) capacitor is usually in order of 10 fF. The adjustment on the tuning range is another advantage as well, which is easily controlled by a course programmable capacitor array. Also the circuit is less prone to parasitic as large offset capacitor is used.

Great care is required when choosing the offset capacitance as it can load the voltage at the summing node. Ideally the offset capacitor should be much smaller than the MEMS static capacitance.
3.2. MEMS Accelerometer

Figure 2(a) and (b) shows a SEM view of the accelerometer [5], which was tested with proposed calibration scheme. The 300 nm capacitive gap is utilized as a sensing electrode to provide large electro-mechanical coupling that result in improved sensitivity. The fingers on each side of the proof-mass are damping electrodes that ensure stable operation of accelerometer, which is operated under low-pressure level to have a low mechanical noise and compatibility with other resonant-type devices. The output response on figure 4(c) and (d) shows a stable response although operating pressure was less than 10 Torr.

The capacitance profile of the sensor was measured using Agilent E4980A LCR meter through probing. The electrostatic force was applied to actuate the proof-mass, and its movement was captured as a capacitance. The equation (4) shows that the displacement has square root relationship with the applied voltage.

\[
F_{\text{spring}} = F_{\text{elec}}, \quad Kx = \frac{1}{2} \frac{\varepsilon_0 A}{d(x - x_0)^2}, \quad \Delta x = \frac{1}{2} \frac{\varepsilon_0 A}{2 K d^2} V^2
\]

Figure 5 depicts a measured capacitance to voltage (C-V) plot on different electrodes. Although each electrode is identical, there is a mismatch that goes as high as 40 fF, which is caused by the parasitic of the sensor. The C-V characteristic of total 55 devices was measured to figure out statistical capacitance distribution. The histogram on figure 6 shows that the variation can be large as 700 fF although all sensors have identical design.

Fig. 4. SEM view of the (a) MEMS accelerometer and (b) 300nm lateral capacitive gap, measured waveform under (c) shake and (d) tilt test; The response does not experience any ringing behavior although operating pressure is 1-10 Torr.

From these measurements, we can conclude that the capacitance mismatch of the sensor will be few hundreds of fF. Assuming the sensor sensitivity is 5 fF/g, the 40 fF mismatch on figure 5 corresponds to 8G of zero-g offset level, which is a critical issue.

![Capacitance mismatch](image)

Fig. 5. Changing MEMS capacitances with applied voltage; The mismatch between electrodes goes as high as 40 fF.

![Statistical distribution](image)

Fig. 6. Statistical distribution of the electrode capacitance (C_p1) among 55 devices; Although the sensor design is identical, the maximum variation becomes as large as ~700fF.

4. MEASUREMENT RESULT

The calibration block was implemented on a printed circuit board (PCB) using a discrete component, and connected with interface ASIC [6] (TSMC 0.18 um) as well as wafer-level packaged (WLP) accelerometer using bond-wire as in figure 7. As an initial step, the offset level of the sensor was tuned by changing calibration signal from 720 mV to 2.3 V. The waveform at figure 8 shows the output changes with different tuning voltage, having total variation of 439.1 mV. This value corresponds to the capacitance matching range of 1.1 pF and tuning resolution of 18.5 fF.

The offset cancellation procedure starts by setting the CV_gain at minimum and changing the calibration voltage. When the output stays on the V_min level (=1.5 V), the CV_gain was increased one step higher and the offset was tuned again. After a number of consecutive steps, the output of the calibrated accelerometer was 1.471 V under maximum gain of 25 mV/\text{fF}. The offset level is 29 mV, which is equivalent to capacitance mismatch of 1.1 fF. Assuming initial variation is 40 fF, proposed calibration method suppressed the offset 40 times more.
The scale factor between calibrated and un-calibrated accelerometer is shown on figure 9. When sensor is un-calibrated, the offset is so large that the gain is limited to 2.5 mV/fF, resulting scale factor of 30.5 mV/g. After the calibration, the mismatch is canceled out fully, resulting increased scale factor of 271.49 mV/g, which is 10 times higher than initial value.

In order to investigate minimum capacitive resolution that proposed method can achieve, the offset capacitor is replaced to 100 fF and step calibration voltage was reduced to 2.5 mV. The overall tuning range reduces to 40 mV, but sub-fF resolution is achieved. This configuration would be ideal for applications that require stringent specification for capacitance mismatch.

The noise spectrum of the accelerometer is shown on figure 10, showing a 20 dB improvement in overall sensitivity. The 5 dB increase in noise floor of the calibrated design is caused by the calibration signal from the noisy microcontroller. This issue is fixed by replacing voltage source with less noisy component.

5. CONCLUSION

A novel offset calibration method is presented in this paper. By using voltage as a calibration signal, the need for large capacitor array is eliminated. Furthermore the range and the resolution are easily set through changing the offset capacitor and tuning voltage steps. Measurement result on different configuration validates the effectiveness of the proposed method and it can be an effective solution to deal with the non-idealities existing inside the sensor.

REFERENCES


AUTHOR CONTRIBUTIONS

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