2001년도 대한전기학회 하계학술대회 논문집 2001.7.18-20

정전형 MEMS 검출기의 새로운 Offset 보상 방법

민동기, 전종업
MEMS Lab., 삼성종합기술원

New Offset-compensation Technique for Capacitive MEMS-Sensor

Dong-Ki Min and Jong Up Jeon
MEMS Lab., Samsung Advanced Institute of Technology

Abstract - An offset problem caused by the static parasitic capacitors is analyzed and then some techniques to reduce their effect on the capacitive position sensor are presented. Also new offset compensation technique is proposed that by adjusting the magnitudes of the modulating signals independently, the charge imbalance between electrodes caused by the parasitic capacitors is eliminated without sensor gain variation. Simulation results are given to validate the proposed compensation technique.

1. INTRODUCTION

Capacitive MEMS-sensors are frequently used to detect some physical quantities such as force, pressure, angular velocity, acceleration, displacement and so on, because of their structural simplicity and reliability, high sensitivity, and ease of sensing[1]. They all detect the capacitance variation which is directly related to how far the proof mass to move from its initial point, and then the physical quantity of interest can be inferred from it. Therefore it is very important to detect the capacitive variation exactly. However, the static parasitic capacitors cause an offset problem and sensor saturation[4][5]. In this paper, some techniques to compensate the effect of various parasitic capacitors are reviewed briefly. Also new compensation technique is proposed using the modulating signals of different magnitudes without any variation of the sensor gain. Simulation results are given to validate the proposed compensation technique.

2. CAPACITANCE SENSING

2.1. Sensing Principle

The principle of capacitive sensor starts from detecting the variation in capacitance. The proof mass or moving mass which can be movable in the designed axis, consists of one of the electrodes of the capacitor and the other electrode is fixed to substrate. This variable capacitor works as a sensor. There are several sources of the capacitive variation[1] but in general the change of the overlapped area between the electrodes is used for the position sensing since the relationship between the capacitive variation and the positional variation is almost linear with large range. Also using a differential structure, more linearity can be obtained. Since force, pressure, angular velocity or acceleration which causes the proof mass to move from its initial position is proportional to the positional variation, therefore these quantities can be known through detecting the capacitance variation.

2.2. Capacitive sensor

In general, capacitive sensor consists of the modulating-signal generator, interface circuit, and demodulator. The modulating signal can be sinusoidal or square wave and its frequency is high enough not to excite the mechanical system. Interface circuit can be high-Z or low-Z amplifier[1]. The high-Z amplifier, usually called as voltage follower, senses the potential of the proof mass since the capacitor bridge acts as capacitive voltage divider in this case. The low-Z amplifier, usually called as charge amplifier, senses the current flowing out of the proof mass and converts into voltage. Since the change in capacitance due to the positional variation is amplitude-modulated, it must be demodulated. The demodulators can be synchronous type or not. The synchronous demodulator needs a phase-shifted signal that is needed to synchronize to the modulated signal to obtain the sensing signal in maximum without error. The asynchronous demodulator is simply a rectifier (See Fig.1).

In force-feedback type capacitive sensor or electrostatic actuator applications, it is desirable to use the equivalent capacitor of the capacitive sensor for both driving and sensing since the sensing signal can be obtained in maximum in the given device area as well as the electrostatic force. A capacitor or a resistor may be included according to the driving and sensing scheme.

The sensing scheme in which a sample-and-hold

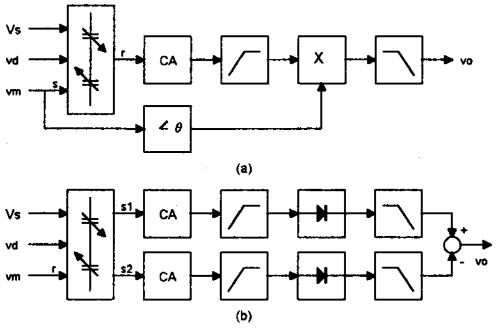

Fig. 1. Block diagram of Sensing Schemes (a) synchronous type (b) asynchronous type. CA means a charge amplifier.

(S/H) is used as a demodulator is shown in Fig. 2. It belongs to the synchronous demodulator since it needs a timing logic circuit to control the S/H. In this paper, only S/H type sensing circuit is considered in compensating the offset problems caused by static parasitic capacitors, but the analysis and the compensation technique mentioned in this paper can be applied to other sensing schemes.

3. S/H-TYPE CAPACITIVE SENSOR

A differential capacitive sensor and its equivalent circuit are given in Fig. 2(a). The proof mass forms the common node of the two capacitors c_1 and c_2, and the displacement x has the relationship with the capacitive variation c_Δ as

$$c_\Delta = (\partial c_1/\partial x)x = -(\partial c_2/\partial x)x = (\partial c/\partial x)x. \qquad (1)$$

To explain the operation principle of an S/H-type capacitive sensor, its schematic diagram of an ideal operation case is given in Fig. 2(b). The inverting input of CA is directly connected to the proof mass and therefore it is virtually grounded since the non-inverting input is grounded. The equivalent circuit of the capacitive sensor and CA is given in Fig. 2(c). Using the superposition theorem, the output voltage of CA when the input is only the modulating signal can be obtained. Figure 2(d) shows the waveform at each node in Fig. 2(b).

The modulating signal v_{m1}($v_{m1} = 1/2V_m + v_m$) and its complement v_{m2}($v_{m2} = V_m - v_{m1}$) are applied at each stator and they produce the impulse input current of CA in ideal case such as

$$i_{in} = 2c_\Delta \frac{dv_m}{dt} = 2\frac{\partial c}{\partial x}x\frac{dv_m}{dt}. \qquad (2)$$

Note that this equation is valid only if the nominal capacitors of c_1 and c_2 have the same value.

Then the input current in Eq.(2) is converted to a voltage v_{co} decaying out with the time constant $\tau = R_f C_f$. It is proportional to the displacement x but its polarity is alternated twice in the period according to the increasing or decreasing edge of the modulating signal. The S/H holds the CA output voltage at the peak considering its polarity by the S/H control voltage.

4. EFFECTS OF PARASITIC CAPACITORS

Parasitic capacitors can not be neglected and their effects must be analyzed since they affects the circuit performance. Figure 3(a) shows the equivalent circuit of the capacitive sensor and CA with possible parasitic capacitors: the parasitic capacitors between the stators C_{p12} , between the stator and the rotor C_{p1} and C_{p2}, between the stator and the ground C_{ps1} and C_{ps2}, and between the rotor and the ground C_{pr}.

By the virtual short circuit property of the op amp, the potential of the inverting node is zero and therefore the effect of C_{pr} is negligible. Also the parasitic capacitors C_{ps1}, C_{ps2}, and C_{p12} are negligible since they are directly connected to the voltage sources. However the parasitic capacitors C_{p1} and C_{p2} are not the case. Consider the current i_{in} in Fig. 3(a). This current is the sum of the current flowing into c_1, c_2, C_{p1} and C_{p2} by KCL. Using the superposition theorem(see Fig. 3(b)), the input current i_{in} can be obtained as

$$i_{in} = 2c_\Delta \frac{dv_m}{dt} + (C_{p1} - C_{p2})\frac{dv_m}{dt}. \qquad (3)$$

Compared with Eq. (2), the second term, the difference between the parasitic capacitors $C_{p1} - C_{p2}$ appears in Eq. (3). This contributes the offset in the output voltage of CA.

5. OFFSET COMPENSATION

5.1. Conventional Methods

The offset problem can be compensated by several methods. They are classified with respect to where the compensation signal to be injected as shown in Fig. 4. Method 1 is very common method that the same amount of the offset is abstracted. However, there may be some saturation in the circuit before the output stage according to the amount of the offset. In method 2, compensation current is injected through a capacitor and then the offset component in the input current of CA is compensated. This type of the offset compensation can be inferred from [3]. As an

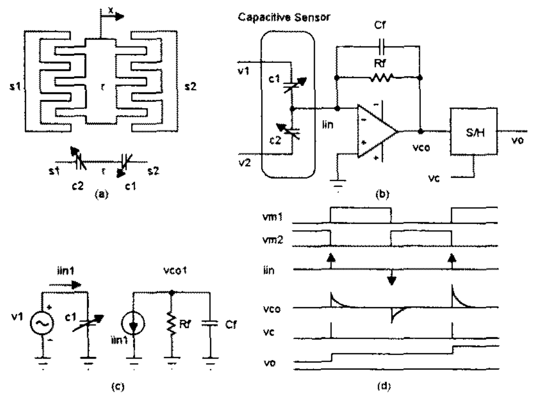

Fig. 2. S/H-type capacitive sensor (a) differential capacitive sensor (b) interface circuit (c) its equivalent circuit (d) some waveform illustrating the operation principle.

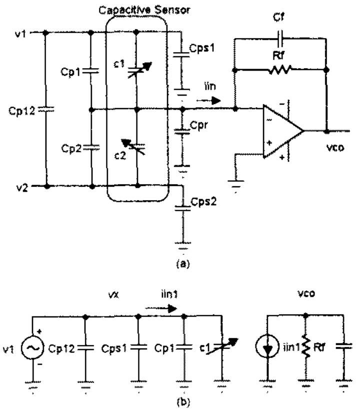

Fig. 3. Sensor with the parasitic capacitors (a) schematic diagram (b) equivalent circuit.

equivalent approach, compensation capacitors can be used by shunting to the side where the parasitic capacitor is smaller than the other. However it is bulky and cumbersome. Method 3 uses a compensated modulating signal which is injected before the capacitive sensor. This type of compensation can be found in [4][5] but the sensor gain is changed by the parasitic capacitors[5].

5.2. Proposed Method

The compensation method proposed in this paper belongs to the Method 3 in Fig.4 and uses asymmetrical modulating signals of which the amplitude can be adjusted independently. They are defined as $v_{m1}=\alpha(V_m/2+v_m)$ and $v_{m2}=\beta(V_m/2-v_m)$. Then the input current can be obtained as

$$\begin{aligned} i_{in} &= [\alpha(C_o+C_{p1})-\beta(C_o+C_{p2})]\frac{dv_m}{dt} \\ &+(\alpha+\beta)c_\Delta\frac{dv_m}{dt} \end{aligned} \tag{4}$$

The first term in Eq. (4) is the offset component and the second is the position sensing term. To make the offset component zero and to have the same gain to the ideal case of Eq. (2), the conditions $\alpha(C_o+C_{p1})=\beta(C_o+C_{p2})$ and $\alpha+\beta=2$ must be satisfied simultaneously. Solving these two equations above, the following gains can be obtained:

$$\begin{aligned} \alpha &= 2(C_o+C_{p2})/D \\ \beta &= 2(C_o+C_{p1})/D \end{aligned} \tag{5}$$

where $D=2C_o+C_{p1}+C_{p2}$.

Therefore these modulating signals can compensate the offset without the sensor gain variation.

6. SIMULATION RESULTS

To validate the proposed compensation technique, the S/H-type capacitive sensing scheme without and with compensation is simulated using SPICE. The comb-type accelerometer, CA, and S/H are modeled using their behavioral models[2]. Table 1 shows the system parameters. The waveforms of the output voltage of CA and the sensor output without compensation are shown in Fig.5(a) and (b) respectively and they show the deteriorated performance and offset problem. With the proposed compensation method, the simulation waveforms are given in Fig. 6(c) and (d). We can see that the offset voltage is eliminated through the proposed compensation technique.

7. DISCUSSION

The proposed compensation can be applied whether sinusoidal or square modulating signals is used. Also it can be applied when the demodulator used is a synchronous or asynchronous type, since the proposed compensation method is derived from the fact that the charges due to one modulating signal must be equal to the other. Most of all, the parasitic capacitance must be made as small as possible before the compensation technique is applied. When S/H demodulator is used, this is critical since it uses the one portion of the modulated signal and therefore it may be more sensitive than other techniques.

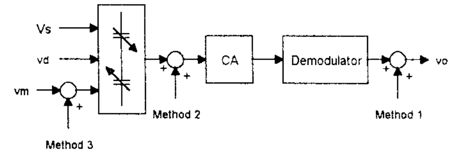

Fig. 4. Offset compensation methods.

8. CONCLUSION

The offset problem due to the parasitic capacitors is analyzed and some experimental waveforms are given. Using the modulating signals of different magnitudes, the offset voltage is fully eliminated without any gain variation.

ACKNOWLEDGEMENT

This work was supported by the National Research Laboratory Program.

REFERENCES

[1] L.K. Baxter, *Capacitive sensors: design and applications*, IEEE press, 1997.

[2] J.A. Connelly and P. Choi, *Macromodeling with SPICE*, Prentice Hall, Inc., 1992.

[3] N. Karlsson, "A study of a high-resolution linear circuit for capacitive sensors," *IEEE Trans. on Instrum. and Meas.*, Vol. 48, No. 6, pp 1122~1124, 1999.

[4] S.A. Valoff *et al*, "Self-balancing interface circuit for presettable micromachined MEMS accelerometers," *IEEE Transducers 99*, pp. 814~817, 1999.

[5] A.H.Falkner, "The use of capacitance in the measurement of angular and linear displacement," *IEEE Trans. on Instrum. and Meas.*, Vol. 43, No. 6, pp 939~942, 1994.

Table 1. System parameters.

Parameter	Value	Parameter	Value
C_{p1}	9.5pF	a	1G@200Hz
C_{p2}	10.4pF	C_f	2pF
C_o	18.888pF	R_f	1e+6Ω
M	2.7e 6kg	α	1.0156044
ζ	0.04	β	0.9843956
K	1.97e+3N/m	v_m	1V@50kHz

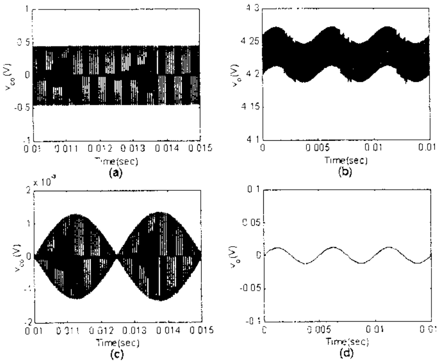

Fig. 5. Simulation results (a) v_{co} without compensation (b) v_o without compensation (c) v_{co} with compensation (d) v_o with compensation