Micro capacitance detection circuit for MEMS capacitive sensor

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Abstract: With the development of micro-electro-mechanical system (MEMS) technology, the MEMS-based capacitive sensor has been widely applied in the field of electron components. However, the capacitance of the micromachined sensor is so small that the detection of the smaller value change of the capacitance is a great challenge. Based on the principle of charging and discharging of the capacitor, a kind of pulse width modulated differential circuit is introduced in this paper. For subsequent amplification, a modified amplifier is presented. The differential circuit converts the weak capacitance change to the change of the pulse width of the output voltage, and the linear relationship can be obtained. And the modified amplifier implements the processes of amplification and filtering synchronously, and a large DC output voltage can be obtained by the low-pass filter. The designed circuits have advantages as simplified circuit, high voltage stability, perfect linearity and resolution. Besides, it is feasible to be integrated with the sensor to largely reduce the transmission error and interference.

Key words: capacitive detection; capacitance transform; width modulation differential circuit; modified amplifier

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0 Introduction

As an important branch of research and fabrication of micro-electro-mechanical system (MEMS), the MEMS-based capacitive sensor has been widely applied in the fields of aerospace, industrial automation, engineering safety monitoring system, etc[1,2]. Capacitive sensor is applied to convert the variation of non-electric quantity and capacitance value. Its advantages are significant as simple structure, high resolution, low demands for applying environment, etc[3]. However, the capacitance of the micromachined sensor is so small, generally a magnitude of pF, that the detection of the smaller value change is also a great challenge. So a conversion circuit is necessary to transform the capacitance change to signals of frequency, voltage or current.

1 Conversion method of micro capacitance in detection circuit

There are two common circuits are applied to converting the weak capacitance change to frequency change.

One is the resonant circuit[4], formed by the MEMS capacitive sensor, inductance and a few external components. It is easy for measurement and has simple structure, but precision and frequency stability are relatively poor and the temperature drift is difficult to be suppressed.

Another kind is shown in Fig. 1[5], including a measured capacitance C_s and a reference capacitor C_r. The capacitance-to-frequency (C/F) conversion module is a relaxation oscillator composed of a constant-current source, complementary metal oxide semiconductor (CMOS) analog switches, a Schmit trigger and some inverters. The D-flip flop produces the difference-frequency signal of different frequency pulse generated by charging and discharging of the two capacitors. But the problem is that the charging current for C_s and C_r must be very consistent with each other and extremely steady during the operation[6], which requires complex design and process of the circuit. Furthermore, the farther f_s deviates from f_r, the bigger the error will be.

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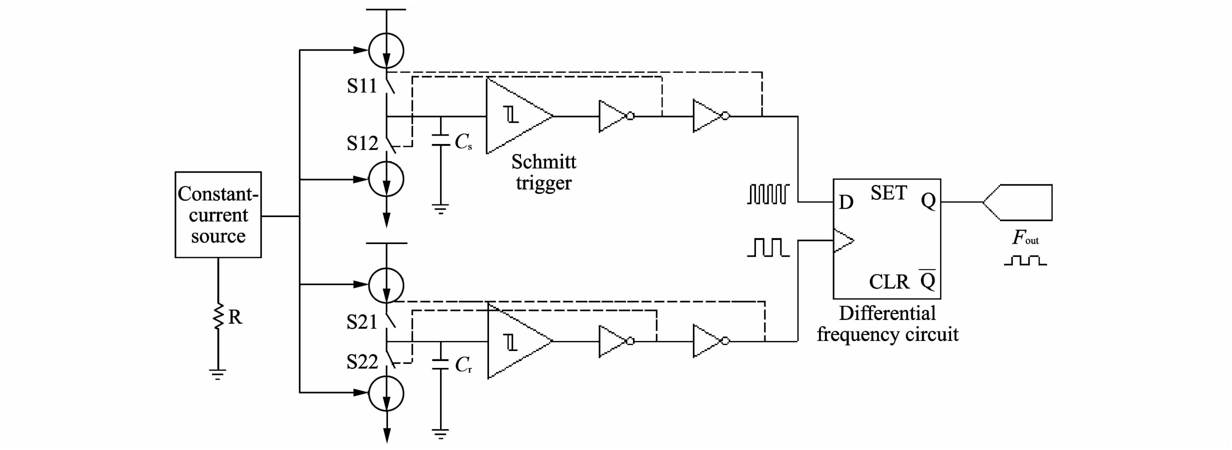


Fig. 1 Schematic diagram of C/F conversion module

Using the pulse width modulation differential circuit for capacitance detection is relatively applicable. This kind of detection circuit has a high resolution and ideal linearity[7]. Based on the principle of charging and discharging of the capacitor, a kind of pulse width modulated differential circuit is introduced in this paper. This circuit can convert the weak capacitance change to the change of the pulse width of the output voltage, and the linear relationship can be obtained. Furthermore, the designed circuit is compatible with traditional CMOS processes and feasible to integrate with the capacitance sensor.

The detection circuit based on the principle of charging and discharging of the capacitor is shown in Fig. 2. The C_x is the measured capacitance and C_{s1}, C_{s2} are parasitic capacitances. The CMOS switches S_1 to S_4 are controlled by a square signal, where S_1, S_4 and S_2, S_3 are synchronous respectively to implement charging and discharging of C_x. Each period of the signal implements a primary circulation of charging and discharging.

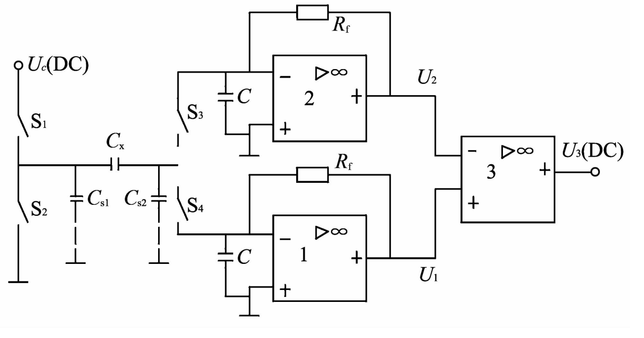


Fig. 2 Logic diagram of capacitance charge-discharge detection circuit

When the switches S_1 and S_4 are closed while S_2 and S_3 are off, C_x is charged by DC voltage source U_c. The charging current flows into the amplifier A_1 with a negative feedback resistor R_f. The quantity of electric charge is

$$Q_1 = U_c \cdot C_x. \tag{1}$$

If the charging frequency is f, the charging current will be

$$I_1 = f \cdot Q_1 = f \cdot U_c \cdot C_x. \tag{2}$$

So the output of operational amplifier A_1 is

$$U_1 = - f \cdot U_c \cdot C_x \cdot R_f. \tag{3}$$

During the process of discharge, S_1 and S_4 are off while S_2 and S_3 are closed and the stored charge of C_x will be released. As the similar principle, the output voltage of the operational amplifier A_2 is

$$U_2 = f \cdot U_c \cdot C_x \cdot R_f. \tag{4}$$

Denoting the gain of A_3 as K, the final output voltage can be obtained as

$$U_3 = 2Kf \cdot U_c \cdot C_x \cdot R_f. \tag{5}$$

It can be seen from Eq. (5) that the output V_3 is proportional to the measured capacitance C_x.

The greatest advantage of the circuit is that it is insensitive to the parasitic capacitances. In the process of charging and discharging, the parasitic capacitance C_{s1} is connected to DC voltage U_c or grounded directly, which will not influence the current in both states. In addition, due to the feature of virtual ground of operational amplifier, C_{s2} also has no effect on the circuit. So the circuit has strong performance of suppressing stray capacitance[8].

In the following, the differential pulse width modulation circuit is applied to the detection of weak capacitance change according to the principle of charging and discharging of capacitance.

2 Differential pulse width modulation circuit

Based on the principle of capacitor charge and discharge detection circuit, the pulse width modulation differential circuit is shown in Fig. 3[9,10]. A measured capacitance C_s and a reference capacitor C_r are used in this circuit. Compared with the circuit shown in Fig. 2, the design of differential arrangement can perfectly suppress environmental disturbance such as zero drift, temperature drift, etc.

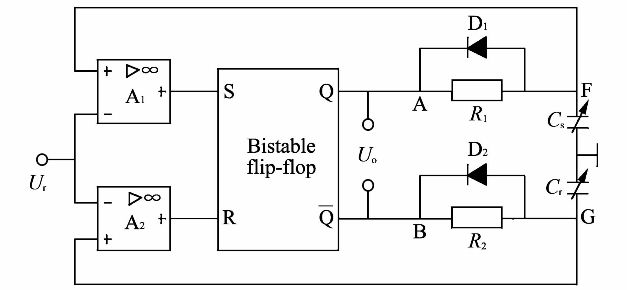


Fig. 3 Differential pulse width modulation circuit

After being powered on, the point A in the circuit is in a high level while B is in a low level. The output voltage of point A charges C_s through R_1 until the potential of point F is equal with reference voltage U_r. At this time, the output of comparator A_1 makes the flip-flop turn over, which leads to a low level for point A and a high level for point B. So C_s begins to discharge through the diode D_1 and the output voltage of point B charges C_r through R_2 until the potential of point G is equal with reference voltage U_r. Then the output of comparator A2 makes the flip-flop turn over again and results in the overturn of the potential of point A and B. So C_r begins to discharge through the diode D_2. By repeating this cycle, a rectangular pulse output, of which the pulse width is modulated by C_s and C_r, can be obtained from the point A and B, respectively. When C_s is equal to C_r, the mean value of U_{AB} is zero as shown in Fig. 4(a). But if C_s has a weak change ΔC, the relative charging time constant of C_s and C_r will be different, the voltage DC components of point A and B are

$$U_A = \frac{T_1}{T_1 + T_2} U_1,$$

$$U_B = \frac{T_2}{T_1 + T_2} U_1. \tag{6}$$

Accordingly, the mean value of output U_{AB} is no longer zero. After low pass filtering, the *DC* voltage output U_o can be obtained as

$$U_o = U_A - U_B = \frac{T_1 - T_2}{T_1 + T_2} U_1. \tag{7}$$

In the above Eq. (6) and (7), T_1 and T_2 are the time required for C_s and C_r charging to U_r, which can be expressed as

$$T_1 = R_1 \cdot C_s \cdot \ln \frac{U_1}{U_1 - U_r}, \tag{8}$$

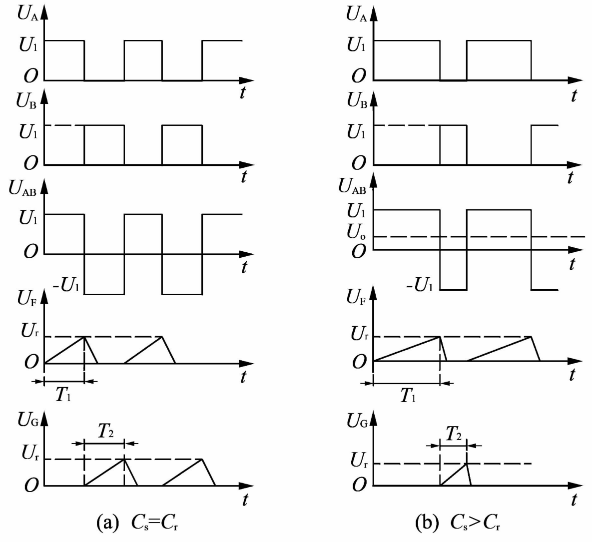
$$T_2 = R_2 \cdot C_r \cdot \ln \frac{U_1}{U_1 - U_r}. \tag{9}$$

If R_1 is equal to R_2 and substitute them in Eq. (7), it can be got as

$$U_o = \frac{C_s - C_r}{C_s + C_r} \cdot U_1 = \frac{\Delta C}{C_s + C_r}. \tag{10}$$

Up to this point, the desired linear relation between ΔC and output voltage is obtained as Eq. (10). Fig. 4(b) shows the voltage waveforms when C_s is bigger than C_r.

The weak change of capacitance of the MEMS-based capacitive sensor, generally 1 fF to 100 fF, can only slightly affect the width of the output rectangular wave pulses. And in each period, both the front and back edge of the two pulses are always corresponding respectively[11]. By this way, the detection can be implemented with a high signal-to-noise ratio and the following signal processing circuit may simply aim at dealing with the small change of the pulse width.



(a) $C_s = C_r$ (b) $C_s > C_r$

Fig. 4 Voltage waveforms of pulse width modulation differential circuit

3 Signal processing circuit

In order to amplify the output signal with high precision, an instrumentation amplifier is used as the amplifier stage. In this paper, the instrumentation amplifier is improved to realize amplification and filtering synchronously, which will simplify the whole circuit to a great extent. The modified circuit is shown in Fig. 5, of which the two in-phase amplifiers with high input impedance in front are changed into two identical Butterworth low-pass filters, so that the output pulse can be filtered while being amplified.

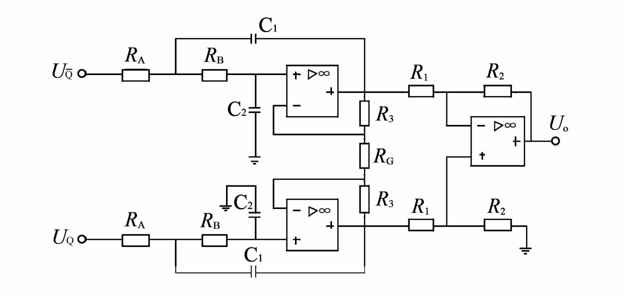


Fig. 5 Modified instrumentation amplifier circuit

As shown in Fig. 5, the input U_Q and $U_{\bar{Q}}$ are connected to the output of U_A and U_B of the differential pulse width modulation circuit respectively. The gain of the modified circuit is not affected by the modification, of which the gain can be obtained by analyzing the classical instrumentation amplifier shown in Fig. 6[12].

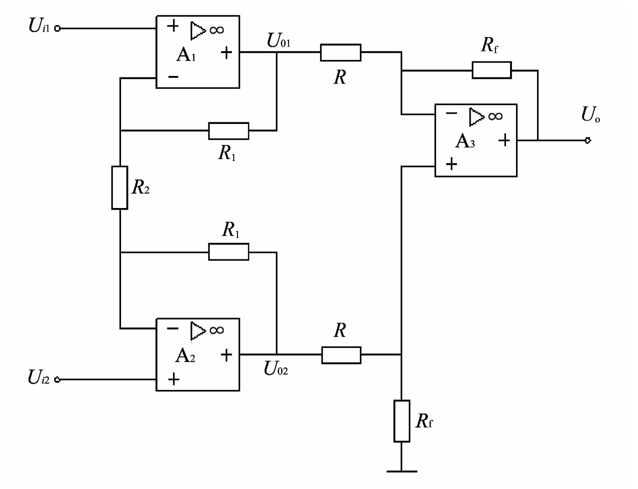


Fig. 6 Classical instrumentation amplifier circuit

Since the differential amplification circuit on left side is entirely symmetrical, the midpoint of R_G can be regarded as virtual ground. So the equations can be got as

$$\frac{U_-}{1/2R_2} = \frac{U_{o1} - U_-}{R_1},$$

$$U_+ = U_- = U_{i1}. \tag{11}$$

So output voltage U_{o1} is got as

$$U_{o1} = \left(1 + \frac{R_1}{1/2R_2}\right) U_{i1}. \tag{12}$$

Similarly, U_{o2} is

$$U_{o2} = \left(1 + \frac{R_1}{1/2R_2}\right) U_{i2}. \tag{13}$$

So the final output voltage is

$$U_o = -\frac{R_f}{R}\left(1 + \frac{R_1}{1/2R_2}\right)(U_{i1} - U_{i2}). \tag{14}$$

Based on the above analysis, the DC differential-mode gain of the modified instrumentation amplifier is

$$A_u = \left(1 + 2\frac{R_3}{R_G}\right) \cdot \frac{R_2}{R_1}. \tag{15}$$

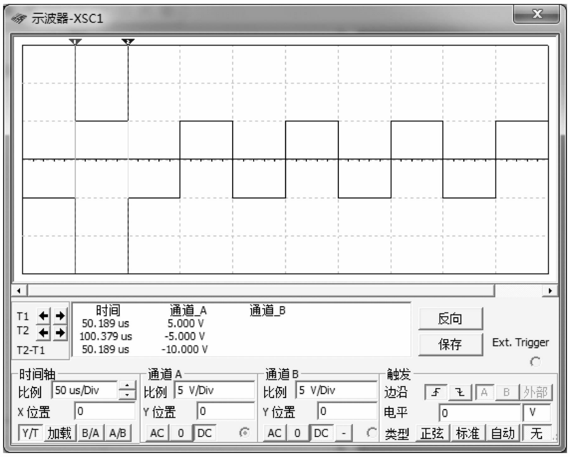
The filtering process is synchronously with amplification in the modified instrumentation amplifier. By filtering the amplified signal U_{AB}, a DC signal can be obtained in the output which is a linear relationship with the ΔC according to Eq. (9). The signal-processing circuit implements amplification and the conversion of rectangular wave pulse U_{AB} and the final DC output.

4 Results

For the further verification of the superiority of this circuit, the circuit is simulated as follows. Fig. 7 shows the simulation result of the pulse width modulation differential circuit. In the simulation, the high level voltage U_1 is designed as 5 V and C_s and C_r are 10 pF, respectively. The detectable weak change of capacitance is ±4 fF, which shows that the detecting resolution has reached a magnitude of fF.

Due to the resolution of the front-end detection circuit has reached a magnitude of fF, gain A_u can be designed as 100, which will meet the detection requirement for the MEMS capacitive sensor. As shown in Fig. 8, the output of low-pass filter is a DC signal by designing parameters of the components appropriately, which is a linear relationship with

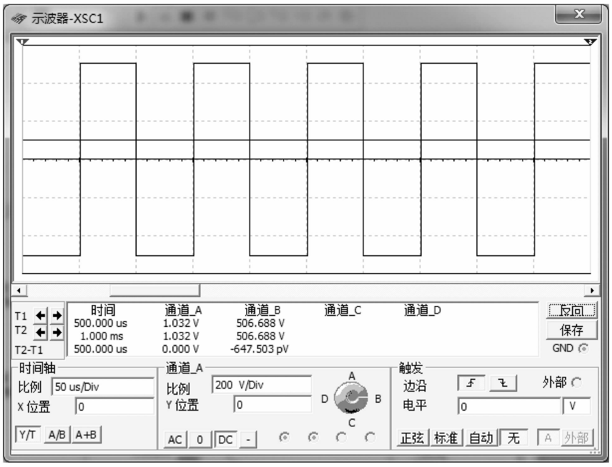
ΔC.



	时间	通道_A	通道_B
T1	50.189 us	5.000 V	
T2	100.379 us	-5.000 V	
T2-T1	50.189 us	-10.000 V	

时间轴 比例 50 us/Div X 位置 0
通道 A 比例 5 V/Div Y 位置 0
通道 B 比例 5 V/Div Y 位置 0
触发 边沿 电平 0 V 类型

Fig. 7 Simulation result of pulse width modulation differential circuit



	时间	通道_A	通道_B	通道_C	通道_D
T1	500.000 us	1.032 V	506.688 V		
T2	1.000 ms	1.032 V	506.688 V		
T2-T1	500.000 us	0.000 V	-647.503 pV		

时间轴 比例 50 us/Div X 位置 0
通道_A 比例 200 V/Div Y 位置 0
触发 边沿 外部 电平 0 V

Fig. 8 Simulation result of amplified signal U_{AB} and final DC output

5 Conclusion

The designed circuit introduced in this paper has successfully implemented the capacitance detection of MEMS capacitive sensor. This circuit converts the weak capacitance change to the change of the pulse width of the output voltage, which makes the detection be implemented with a high signal-to-noise ratio, and a desired linear relationship can be obtained. The modified instrumentation amplifier can implement amplification and filter synchronously, which simplifies the whole circuit and lower the cost. Furthermore, the designed circuit is compatible with traditional CMOS processes and feasible to integrate with the capacitance sensor.

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