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The Study of a Digital Equivalent Capacitor Circuit

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Abstract

Resistors, inductors and capacitor are indispensable components in modern electronics field. While digital potentiometer is capable of conducting digital adjustments on resistances, the flexibility of adjusting the capacitance of most capacitors is still very limited even until now. This paper introduced a digital capacitor circuit based on impedance transformations. The impedance transformation circuit was set up by assembling an integrated operational amplifier and small amounts of resistors and capacitors. The capacitance of this circuit can be adjusted by controlling the resistance of a certain resistor using a digital potentiometer. Simulation results showed this circuit has many advantages including great flexibility if controlled with a single chip, wide capacitance adjustment range, insensitivity to temperature and pressure, and the size of the circuit remaining the same while the capacitance increases.

Keywords: *Programmable; Digital capacitor; Impedance transformation*

1. Introduction

As the electronic technology develops, there are significantly increasing needs of digital programmable devices in this field. Now days, there are few digital adjustable capacitor products in the market. Most of available capacitors use simple analog switches to control the capacitance. This kind of capacitor has many disadvantages including size limitation and narrow adjustment range (only several to less than 20 pF). Also, most equivalent capacitor circuits consist of capacitors and resistors connecting in series or parallel instead of just capacitors alone. This narrows the freedom of the resistor in the circuit and subsequently limits the range of the equivalent capacitance. The digital capacitor introduced in this paper, using impedance changing circuit, yields pure capacitance equivalent outputs. In order to make the integration of the circuit easy, the traditional method of directly using analog switches to control the capacitance was abandoned. Instead, the capacitance was controlled by adjusting the resistance in the circuit. Using this method, the equivalent capacitance has large adjustable range and high accuracy, and the size of the equivalent circuit remains the same regardless the value of the capacitance output. This circuit, if adding a single chip to control the output capacitance, has the potential to be widely used in many different kinds of electronic devices.

2. Impedance Generator Principle

2.1. Equivalent Capacitor Circuit

The equivalent capacitor circuit based on an integrator is shown in Figure 1.

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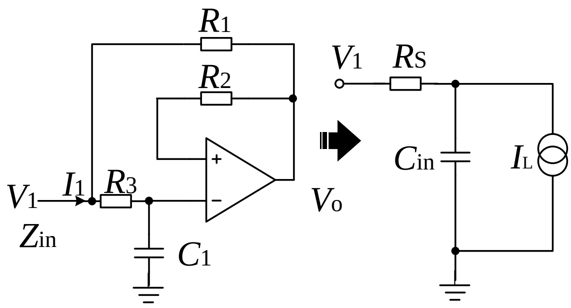

Figure 1. Equivalent Capacitor and Equivalent Circuit

It can be obtained from the circuit above that

$$V_o \cdot j\omega C_1 (R_3 + \frac{1}{j\omega C_1}) = V_1 \quad (1)$$

$$\frac{V_1 - V_o}{R_1} = I_1 \quad (2)$$

Where V_1 and V_0 are the input and output voltages of the equivalent capacitor; $1/ j\omega C_1$ is the capacitance of the capacitor C_1; R_1 and R_3 are the resistances of resistors R_1 and R_3 respectively; I_1 is the input current of the equivalent capacitor.

Combine Equation (1) and Equation (2)

$$R_1 + \frac{1}{1 + j\omega C_1 R_3} = \frac{V_1}{I_1} \quad (3)$$

It can be seen from Equation 3 that the equivalent impedance

$$Z_{in} = \frac{V_i}{I_i} = R_1 + \frac{1}{j\omega C_1 \frac{R_3}{R_1}} \quad (4)$$

Therefore the value of the equivalent capacitance $C_E = C_1 R_3 / R_1$.

I_L is the equivalent leakage current passing through the equivalent capacitor and its value can be calculated using the following equation

$$I_L = \frac{V_{ie} + I_{ie} R_3}{R_1} \quad (5)$$

where V_{ie} is the bias voltage; I_{ie} is the bias current.

An assumption that $R_1 = R_2$ was made while deriving equation (5) to minimize I_L. Leakage current could potentially impact the stability of the capacitor, result electromagnetic problems and/or affect the frequency characteristic of the circuit. A high-quality operational amplifier is usually desirable in order to control the leakage current. Also, the equivalent capacitor would be non-polarized only if the capacitor C_1 is non-polarized. As it can be seen from the equations above, resistor R_1 is important in determining the value of the equivalent impedance Z_{in}; resistor R_2 together with the operational amplifier form an in-phase gain amplifier circuit; R_1 and R_3 together determine the value of the equivalent capacitance C_E.

The value of the input impedance of the equivalent capacitor is computed using the equation below

$$Z_{in} = R_1 + \frac{1}{1 + j\omega C_E} = R_1 + \frac{R_1}{1 + j\omega C_1 R_3} \quad (6)$$

It can be seen from Equation (6), this equivalent circuit, consisting of a capacitor and a resistor connecting in series, is not a pure-capacitance equivalent capacitor.

2.2. Impedance Generator Principle

The impedance transformation circuit which consists of operational amplifiers and resistors is shown in Figure 2.

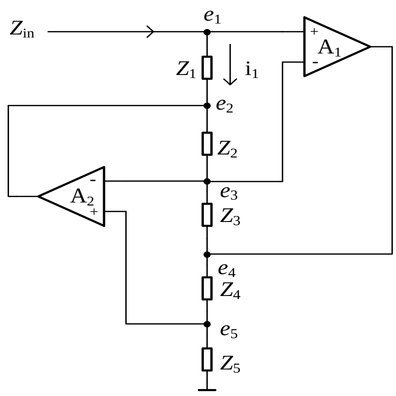

Figure 2. Impedance Converting Circuit

The following equations can be obtained according to Kirchhoff's law (assuming the operational amplifier A_1 and A_2 in Figure 2 are ideal)

$$e_1 = e_3 = e_5 \tag{7}$$

$$\frac{e_1 - e_2}{Z_1} = i_1 \tag{8}$$

$$\frac{e_3 - e_2}{Z_2} = \frac{e_4 - e_3}{Z_3} \tag{9}$$

$$\frac{e_4 - e_5}{Z_4} = \frac{e_5}{Z_5} \tag{10}$$

where e_1, e_2, e_3, e_4, and e_5 are node voltages of the points shown in Figure 2; Z_1, Z_2, Z_3, Z_4 and Z_5 are the resistance values of resistors Z_1, Z_2, Z_3, Z_4 and Z_5, respectively. i_1 is the value of the current passing through resistor Z_1.

According to Equation (7) ~ (10), the equivalent impedance Z_{in} in Figure 2 can be expressed as

$$Z_{in} = \frac{e_1}{i_1} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4} \tag{11}$$

Using Equation (7) to (10), we can also get

$$e_4 = e_1 \left(1 + \frac{Z_4}{Z_5}\right) \tag{12}$$

From Equation (7), (9) and (12), the following equation is obtained

$$e_2 = e_1 \left(1 - \frac{Z_2 Z_4}{Z_3 Z_5}\right) \tag{13}$$

According to Equation (11) ~ (13), it can be known that Z_{in} is proportional to Z_1, Z_3 and Z_5, and inversely proportional to Z_2 and Z_4. Phase and amplitude changes of e_1 are limited by e_2, e_4, Z_2, Z_3, Z_4 and Z_5. In order to let operational amplifier work within its dynamic range, e_4 and e_2 should work within the maximum voltage output ranges of operational amplifier A_1 and A_2, respectively. Therefore Z_2, Z_3, Z_4 and Z_5 together determine the dynamic range of the operational amplifier's output voltages and Z_1 determines the dynamic range of the input currents.

The resistors in this circuit must meet the requirements that the operational amplifier must form a DC loop and the phase change of the negative feedback loop cannot cause oscillation. For example, if Z_1, Z_2, Z_3, Z_4 and Z_5 are all capacitors, the circuit cannot work due to lack of negative feedback loop.

From Equation (11) we can see when $Z_1=R_1$, $Z_2=R_2$, $Z_3=R_3$, $Z_4=R_4$ and $Z_5=1/j\omega C_5$, Z_{in} equals to the impedance of a capacitor with an equivalent capacitance C_E expressed as

$$C_E = C_5 \frac{R_2 R_4}{R_1 R_3} \tag{14}$$

3. Digital Equivalent Capacitor Circuit

The digital equivalent capacitor circuit is shown below in Figure 3.

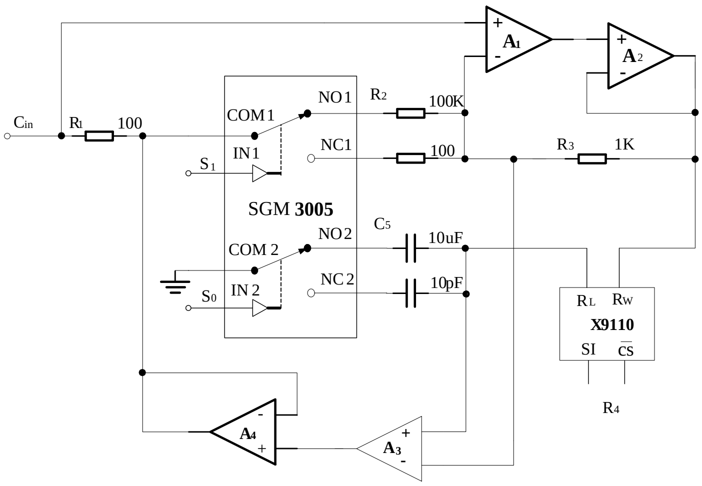

Figure 3. Digital Equivalent Capacitor Circuit

Operational amplifier A_2 and A_4 in Figure 3 serve as buffers. When the equivalent capacitor works within its high frequency range, they increase the output currents of operational amplifier A_1 and A_3. The range of output equivalent capacitance is controlled by the analog switch SGM3005. An X9110 digital potentiometer with an adjustable range of 0–100 $k\Omega$ is used serving as resistor R_4. The X9110's SPI serial port SI is used to adjust the value of the equivalent capacitance. The resistances of resistor R_1 and R_3 are 100Ω and 1$k\Omega$ respectively. The unit of the equivalent capacitance is converted by changing the resistance of resistor R_2 and the capacitance of capacitor C_5 with S_0 and S_1 respectively. The output gears of the equivalent capacitor are shown in Table 1.

Table 1. The Output Gears of the Equivalent Capacitor

S_1S_0	R_2 (Ω)	C_5	Unit of C_E
0 0	100	10pF	pF
0 1	100	10uF	nF
1 0	100K	10pF	uF
1 1	100K	10uF	mF

According to Figure 3 and Table 1, $S=2^1\times S_1+2^0\times S_0$. The equivalent capacitance can be expressed using the following equation

$$C_E = C_5 \frac{R_2 R_4}{R_1 R_3} = D10^{3S-12} \tag{15}$$

where C_E is the equivalent capacitance; C_5 is the capacitance of the capacitor C_5; D is an integer number between 0 and 999.

4. Integrated Chip of the Digital Equivalent Capacitor

An integrated digital adjustable capacitor chip can be achieved by integrating the digital equivalent capacitor in a single chip as shown in Figure 4.

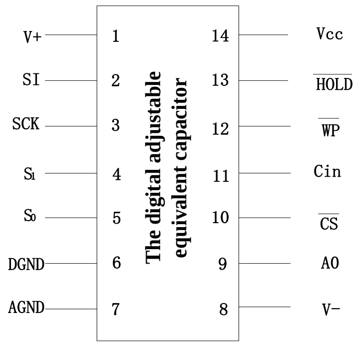

Figure 4. Pins of the Digital Adjustable Equivalent Capacitor

Table 2. Pin Descriptions

PIN	SYMBOL	FUNCTION	PIN	SYMBOL	FUNCTION
1	V+	Analog Supply Voltage	8	V-	Analog Supply Voltage
2	SI	Serial data input	9	A0	Device Address
3	SCK	Serial Clock	10	$\overline{CS}$	Chip select pin
4	S_1	Unit converting controllers	11	Cin	Input of the equivalent capacitor
5	S_0	Unit converting controllers	12	$\overline{WP}$	Hardware Write Protect
6	DGND	Digital ground	13	$\overline{HOLD}$	Device Select
7	AGND	Analog ground	14	Vcc	Power-supply

5. Comparison of Experimental and Simulation Results

The low pass filtering circuits of a real capacity and resistances Figure 5 and the equivalent capacitance and resistances Figure 6 are shown below. The cut-off frequency is

318.42kHZ. Figure 7 shows the frequency amplitude characteristics curve of the real capacitor. Figure 8 shows the frequency amplitude characteristics curve of the equivalent capacitance. The simulation results showed that the amplitude frequency characteristic curves of the equivalent capacitor and the real capacitor fit very well.

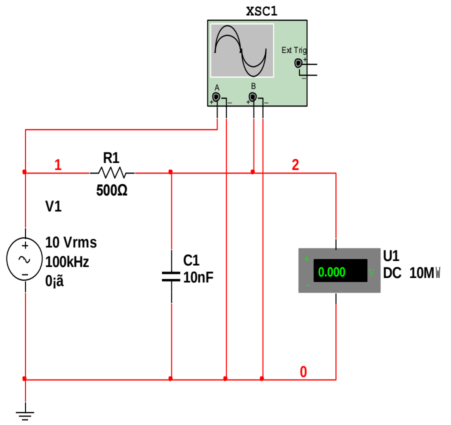

Figure 5. Real Capacity Simulation Circuit

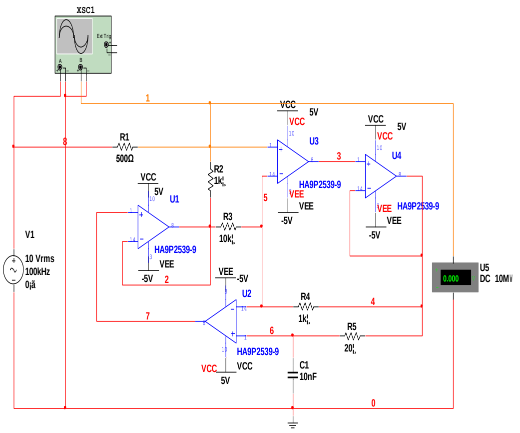

Figure 6. Equivalent Capacitance Simulation Circuit

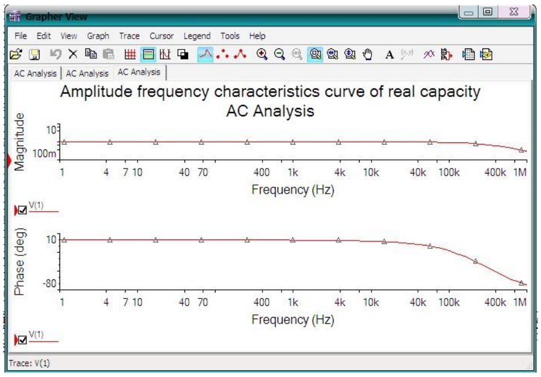

Figure 7. Curve of Real Capacity

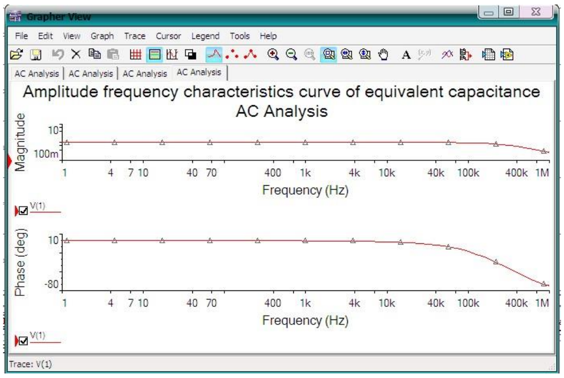

Figure 8. Curve of Equivalent Capacitance

6. Application of Digital Equivalent Capacitor

The circuit of a multivibrator consisting of an NE555 timer and an equivalent capacitor is shown in Figure 9. The charge-discharge capacitor in the multivibrator was replaced by an equivalent capacitor. The oscillating period of the multivibrator is controlled by adjusting the capacitance of the equivalent capacitor CE using a single chip. The single chip used in this paper was ATmega8_06, the serial communication interface (SCI) of which PB3 was connected to the serial interface (SI) of the equivalent capacitor to control the capacitance input. The single chip's pin PB5 was connected to the SCK of the equivalent capacitor to provide clock signal. PC1 and PC2 were connected to S_1 and S_0 respectively to adjust the unit of the capacitance. CS and A_0 were control by PC_4 and PC_3 respectively.

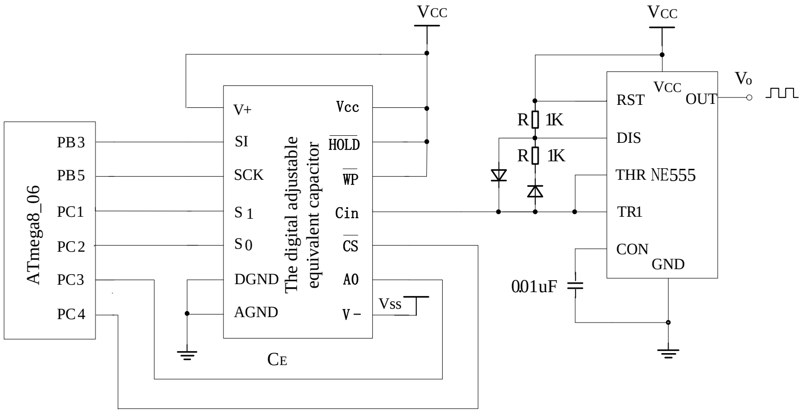

Figure 9. The Multivibrator Consisting of NE555 Timer and Equivalent Capacitor

7. Conclusion

The simulation and experimental results showed that the amplitude frequency characteristics of the equivalent capacitor and real capacitor were basically the same. The differences between the simulation and experimental results can be explained by the non-ideality of the experimental devices such as the operational amplifier. Those differences could be minimized if considering this factor while setting up the circuit. With different amplifiers or circuit settings, different types (*e.g.* with high power, high frequency, high voltage or high precision etc.) of equivalent capacitance circuits can be obtained. Using single chips to control the value of the equivalent capacitance is able to make the equivalent capacitor programmable. This design has the potential to bring great convenience to electronic product designs and scientific researches. Integrating the programmable equivalent capacitor circuit into a single chip as shown in Figure 3, a new programmable capacitor chip will be obtained, which will greatly benefit the field of digital electronic circuit.

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