A period-based measurement for grounding capacitance meter with arduino using a relaxation oscillator

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Abstract. This paper focus on the development of a simple and low-cost capacitance measurement for Arduino microcontroller. The working principle of the circuit is based on the period changes of the square-wave signal, which is generated by relaxation oscillator, causes by RC values in the circuit. The relaxation oscillator is based on two different types of op-amp, rail-to-rail and comparator. The output frequency of the oscillator is about 2 kHz to 100 kHz. The range of test capacitors is approximately from 1 pF to 33 pF. The percent error of each type of op-amp due to nonlinearity and parasitic capacitance is presented. Finally, the comparison of the experimental results and theoretical analysis as well as precision LCR meter are investigated and discussed.

1. Introduction
In the world of instrumentation, capacitance measurement is one of the commonly utilize for sensing environment and physical signals. For example, force, pressure, displacement, liquid level, permittivity, torque, dielectric properties of material, moisture and humidity [1-2]. In capacitive sensors applications, some techniques desired a wide bandwidth in order to improve resolution of output signal [3]. This method tends to be complicated that it included a multiplexer and a Capacitance to Voltage Converter (CVC) before converting voltage to a period time related to capacitive values. Some of them provided a capacitance-to-voltage conversion before measuring with a simple digital volt meter. Acknowledge that capacitance values have to be measured electrically by electronics sensors in several techniques. The significant information form electrodes in capacitive sensors used to connect to specific circuits which can obtain an enough output signals and interpret to capacitance or other parameters, which are proportional to capacitance [4]. To convert capacitance values to electrical signal, there have been many offer electronics circuit interfacing for this issue such as capacitance-to-frequency, phase and duty cycle [1], capacitance-to-digital by analog-to-digital converter and so on. Precise measurement for different capacitance has the ratio in a continuous pattern. This pattern refers to continuous-time voltage sensing, which is a high elaborate output signal without noise interference [5]. Although this method can achieve reduce power consumption and detect capacitance in a very small range, it always need a complex digital logic gate with high frequency clock to handle the process. However, to enhance the performance of data acquisition interfacing circuit, the electronics circuit need to be accurate, a high-resolution, reliable, linearity low power consumption and a low- cost system. Other seriously problems of a large
semiconductor devices have to take into account, such as transistor, are the thermal voltage and parasitic capacitance. These factors cause losing signals through the output [6].

Due to the simple detection for a microcontroller and linearity of the relaxation oscillator [7], this paper proposed a capacitance-to-period converter based on a single supply relaxation oscillator in order to generate a proper digital clock, which has a proportional period to capacitive value, before measuring by the microcontroller. In addition, researchers reported a simple, accurate and low-cost technique interfacing analog circuit for measuring capacitance with a popular microcontroller, Arduino Nano, and display on LCD. Moreover, we compared our proposed instrument with a precision LCR meter – GW INSTEK LCR- 6002 and demonstrated the proposed circuits based on LM311 comparator and TLC2272CP rail-to-rail op-amp.

2. Principle of relaxation oscillator

2.1. Basic concept of relaxation oscillator

![Figure 1. Self-oscillation signal on relaxation oscillator.](image)

In general, relaxation oscillator provides a feedback circuit in order to feed some of output signal to input pin, which is an RC network, Thus the self-oscillation will be employed. Similar to a comparator, the input signal is compared with another input pin. Figure 1 shown the self-oscillation of relaxation oscillator. The red line is output square-wave, according to the charge-discharge voltage of the capacitor, blue line. The two reference levels appear from two situations. First, when output is logic high, the upper threshold: \( V_{UH} \) will limit the charge voltage from the capacitor then switch the output into logic low. Second, when output is logic low, it will discharge the capacitor and lower threshold level: \( V_{LH} \) will limit the discharge voltage voltage then switch the output into logic high again.
2.2. A relaxation oscillator by LM311 comparator

![Relaxation Oscillator Circuit](image)

Figure 2. Illustration of relaxation oscillator circuit based on LM311 comparator.

The single supply relaxation oscillator using LM311 comparator and its output pin is connected to A0 pin on Arduino Nano, shown in figure 2. An automatic charging voltage on the positive pin is more than 0 V, which is upper threshold: $V_{UH}$, and lower threshold level: $V_{LH}$ is between $V_{UH}$ and 0 V. This is called hysteresis [8]. In theory, the upper and lower threshold are function of $R_1$, $R_2$, $R_3$ and $V_{CC}$. The period time ($T$) is given by [9].

$$T = RC \ln \left( \frac{V_{UH} - V_{CC}}{V_{LH} - V_{CC}} \right)$$  (1)

where $RC$ is time constant of RC-network. $V_{UH}$ and $V_{LH}$ are threshold voltage levels as can be seen in equations (2) and (3).

$$V_{UH} = \frac{(R_1 + R_3)R_2V_{CC}}{R_1R_2 + R_1R_3 + R_2R_3}$$  (2)

$$V_{LH} = \frac{R_2R_3V_{CC}}{R_1R_2 + R_1R_3 + R_2R_3}$$  (3)

The nonlinearity may occur with a small capacitance because of the circulation delay on comparator [9]. In practice, the output square-wave of LM311 oscillator achieve to $V_{sat}$, which is approximately $(0.8)V_{CC}$, instead of $V_{CC}$. For this reason, period of the oscillation from LM311 will deviate during interpreting to the capacitance.
2.3. A relaxation oscillator by TLC2272CP rail-to-rail op-amp

To overcome a deviation issue, rail-to-rail op-amp has been employed in this work using TLC2272CP, shown in figure 3. The output of rail-to-rail op-amp is able to achieve the maximum output swing with a single supply voltage \[ V_{cc} \]. The output high and low levels is connected to A0 pin of Arduino that is able to touch \( V_{cc} \) and 0 \( V \), respectively. Therefore, \( T \) in equation (1) demonstrated a linearity with the total capacitance \( C=C_x+C_O \), which is the summation between the capacitance from capacitor \( C_x \) and the offset (parasitic) capacitance \( C_O \) occurred during electronics pins on the circuits. In this circuit, the capacitor will connect between electric ground and negative pin of the op-amp. The resistor \( R \) connected from negative pin and output in order to control the charge and discharge cycle along the period of oscillation. The time-period \( T \) has a linear proportional to \( C \) when we define \( R \) is constant. The component values are as follows: \( R = 5.01 \, \text{M}\Omega, R_1=R_2=200 \, \text{k}\Omega \) and \( R_3=100 \, \text{k}\Omega \). \( R_1 \) was used to generate a symmetry square-wave output by 50% duty cycle, generally it is equal to \( R_2 \). From these values, equation (1) can be evaluate to be

\[
T = 2.2RC. \tag{4a}
\]

The frequency of output square-wave is given by

\[
f = \frac{1}{T} = \frac{1}{2.2RC}, \tag{4b}
\]

The capacitance will be calculated from modifying equation (4a) and given by

\[
C = \frac{T}{2.2R}. \tag{5}
\]

The equation (5) is utilized to estimate the capacitance by measuring the period of the square-wave output connected to the microcontroller. The parasitic capacitance, occurred during no capacitor connected or offset capacitance \( C_O \), comes from a different circuit structure inside each op-amp. It was compensated by subtraction in coding, followed by \[
C_x = \frac{T}{2.2R} - C_O \]
as shown in figure 4.
In figure 4, the resistor, \( R \), is a constant value in coding. To measure \( T_{\text{Hi}} \) and \( T_{\text{Lo}} \), the function \text{PulseIn}(\text{pin}, \text{value}) \) is employed to count the period of the logic signals from analog pin. The value in the \text{PulseIn} function is able to be HIGH for reading \( T_{\text{Hi}} \) and LOW for reading \( T_{\text{Lo}} \).

### 3. Experimental results

To test the performance of each capacitance meter, the ceramic capacitors with the capacitance between 1 pF and 33 pF are measured. Also, the results had to verify with LCR meter model GW INSTEK LCR-6002. The period of square-wave from each of the circuits are measured and compared with LCR-6002, shown in figure 5(a).

As the observation, the proposed circuit from LM311 had some distortion while the test capacitors are increasing. In contrast, the curve of TLC2272CP approach the standard value curve from LCR-6002. It is an evident that the performance of rail-to-rail op-amp is clearly better than comparator op-amp. The percent error of the proposed circuits, compared with LCR-6002 standard LCR meter, is shown in figure 5(b). The percent error from both circuits are high at small capacitance values because of the effect
from unmanageable conditions and noise. However, the errors from TLC2272CP are less than 5% for test capacitors larger than 5 pF.

Figure 6. The variation period of output signal with test capacitors.

Figure 6 demonstrates the period of square-wave signals from each circuits and comparison with theory. As we can see that TLC2272CP curve is close to the theoretical curve more than LM311. However, the proposed circuit from LM311 is able to adjust and compensate in order to raise up curve to fit the theoretical results by adding a signal conditioning properly such as op-amp integrator and differentiator circuits.

4. Conclusion

The performance comparisons between LM311 comparator and TLC2272CP rail-to-rail op-amp has been presented. The proposed circuits shown the benefit of rail-to-rail op-amp for a grounding capacitance meter based on a single supply relaxation oscillator. The output signals had been measured by monitoring charge and discharge time with Arduino microcontroller, compared with LCR-6002 standard LCR meter. The resolution is able to achieve to 1 pF. The circuits developed in this research could be applying for a small value of capacitive sensors. In order to enhance the resolution of capacitance measurement, the circuits will be improved by adding the constant frequency instead of self-oscillation.

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