A. Introduction

This paper discusses the design of a project used in a second year course of Electrical Engineering Technology at Purdue University. The design reviews material that has been covered in the first few analog courses at the University to help students link their knowledge together.

The project uses a variable capacitor that has a rotating plate. The circuit detects the variation in the capacitor. The block diagram of the design is in Figure 1 below.

![Block Diagram of the Project](image)

**Figure 1 – Block Diagram of the Project**

B. The Position Detector Project

1. The Variable Capacitor

The key component of the design is a variable capacitor. It consists of two 8cm by 5cm conduction plates that are place 1mm (0.001m) apart as in Figure 2 on the next page.

The bottom plate is affixed and the top plate rotates about the shaft that results in different plate areas. The capacitance is:

\[
C = \frac{A\varepsilon_r(8.85 \times 10^{-12} \text{ } F / m)}{d}
\]

*Proceedings of the 2002 American Society for Engineering Education Annual Conference & Exposition*  
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In the equation, C is the capacitance in farads, A is the plate area in m², eᵣ is the dielectric constant, and d is the distance between the plates in m. By rotating the top plate, we create a variable capacitor and the design detects this variation.

The plates in this project are double-sided copper clad plates. The two copper sides of each plate are connected together by a wire. When they are 90° apart as in Figure 3, the capacitance is measured to be 95pF.
2. The Oscillator

Since the circuit detects the capacitance variation, an ac signal is needed. A sine wave oscillator meets this need and is the first part of our circuit. The schematic diagram of the oscillator is in Figure 4.

![Figure 4 - The Oscillator](image)

Let $R_2 = R_3 = R$ and $C_1 = C_2 = C_3 = C$, the oscillation frequency is:

$$f = \frac{1}{2\pi RC} = \frac{1}{2\pi (22k\Omega)(0.0015\mu F)} = 4.82kHz$$

In designing the oscillator, the resistors $R_2$ and $R_3$ and the capacitors $C_1$, $C_2$, and $C_3$ are matched within 1% of each other. The potentiometer $R_1$ is a 22-turn trimmer that is tuned so that the circuit oscillates. In our circuit, the value of $R_1$ is approximately 21kΩ.

The output of the first operational amplifier is a sine wave with its peak value of 15V (power supply voltage) and the output of the second operational amplifier is a cosine wave (90° phase shift) with similar peak value. The waveforms of the output voltages are in Figure 5 on the next page.

The output of the first operational amplifier is used as the reference voltage for the following Wheatstone bridge.
3. The Wheatstone Bridge

The schematic diagram of the bridge is in Figure 6 below.

![Diagram of the RC Wheatstone Bridge](image)

The capacitor $C_4$ is the variable capacitor discussed previously. When the plates are 90° apart, the capacitance is 95pF. When the rotational plate is on top of the bottom plate, the capacitance is measured to be 150pF. This capacitor is connected to the bridge via a two-conductor shielded
cable. The reference voltage is the sine wave output from the oscillator. This sine wave has its peak value of 15V and frequency of 4.82kHz.

At 95pF, the capacitive impedance is:

\[ Z_{c4} = -\frac{j}{2\pi (4.82kHz)(95pF)} = -j347.6k\Omega \]

At 150pF, the capacitive impedance is:

\[ Z_{c4} = -\frac{j}{2\pi (4.82kHz)(150pF)} = -j220.1k\Omega \]

With the change of the capacitive impedance of capacitor C4, the voltage v1 also changes its peak and phase values.

The other branch of the bridge consists of another series RC network. In order to balance the bridge, the ratios of capacitances and resistances of the two branches of the bridge must be matched. Since C5 is approximately 1.6 times larger than C4, the series combination of R5 and R6 in the second branch should be 1.6 times larger than R4. To further fine-tune the balancing of the bridge, a 22-turn 10kΩ potentiometer is connected in series with a 15kΩ resistor to obtain the proper ratio of the resistances in the two branches of the bridge.

The two output voltages of the bridge are used as the inputs of an Instrumentation Amplifier.

4. The Instrumentation Amplifier

The schematic diagram of the Instrumentation Amplifier is in Figure 7 on the next page.

In this amplifier, if we let \( R_8 = R_9 = R_{10} = R_{11} \), and \( R_{12} = R_{13} \), the output voltage \( V_3 \) is:

\[ V_3 = \frac{R_{12}}{R_{11}} \left( 1 + \frac{R_8}{R_7} \right) (V_2 - V_1) \]

In the design, the Instrumentation Amplifier has a gain of 31. Note that we must match resistors closely in order for the above equation to be true. In our circuit, \( R_8 \) through \( R_{13} \) are precision resistors.
The output voltages $V_1$ and $V_2$ of the bridge are the input voltages of the amplifier. After connecting the circuit, adjust the potentiometer $R_5$ to obtain the minimum output of the amplifier when the two plates are 90° apart. Ideally, the output voltage of the Instrumentation Amplifier is zero under these input conditions, but because we are using non-ideal components, our circuit exhibits the waveform in Figure 8. The peak-to-peak value of the wave is approximately 80mV. 

![Figure 7 – The Instrumentation Amplifier](image)

![Figure 8 – The Output Waveform of the Instrumentation Amplifier](image)
This wave also rides on a 60Hz signal of 50mV peak-to-peak. This low frequency interference is introduced to the circuit via the connecting cable of the variable capacitor and the power supply unit.

When the two plates are 60°, 30°, and 0° apart, the peak-to-peak values of the output of the Instrumentation Amplifier are 220mV, 360mV, and 520mV respectively.

The output of the amplifier then goes to a Second Order Active Bandpass Filter to amplify the signal more, to condition the signal to produce a perfect sine wave, and to eliminate the 60Hz interference.

5. The Second Order Active Bandpass Filter

The schematic diagram of the filter is in Figure 9 below.

![Figure 9 – The Second Order Active Bandpass Filter](image)

In the circuit, if we let $C_6 = C_7 = C$ and $R_{14} = R_{16} = R_{17} = R$, the center frequency is:

$$f_0 = \frac{\sqrt{2}}{2\pi RC}$$
Since the desired center frequency is 4.82kHz, let C be 0.0039μF, then:

\[ R = \frac{\sqrt{2}}{2\pi (4.82kHz)(0.0039\mu F)} = 11.97k\Omega \]

We use 12kΩ for R_{14}, R_{16}, and R_{17}.

The Q value of the circuit is:

\[ Q = \frac{\sqrt{2}}{4 - K} \]

Where K is closed-loop gain of the Noninverting Amplifier section of the circuit. In the filter, the desired value of Q is 10.

\[ 4 - K = \frac{\sqrt{2}}{10} \Rightarrow K = 4 - \frac{\sqrt{2}}{10} = 3.8586 \]

Let R_{15} be 10kΩ, then:

\[ R_{18} = R_{15}(3.8586 - 1) = 10k\Omega(2.8586) = 28.586k\Omega \]

A 50kΩ 22-turn potentiometer is used in place of R_{18} and it is set to the desired value. In the design, it is best to use precision resistor for R_{15} because a slight variation of the closed-loop gain could result in a huge change in the Q value.

The output voltage V_4 of the filter now is a perfect sine wave and the 60Hz interference is eliminated.

When the plates are 90° apart, the peak value of the sine wave is:

\[ V_{4PEAK} = \frac{V_{3PEAK}(10)(3.8586)}{\sqrt{2}} = \frac{(40mV)(10)(3.8586)}{\sqrt{2}} = 1.1V \]

When the plates are 60° apart, the peak value of the sine wave is:

\[ V_{4PEAK} = \frac{V_{3PEAK}(10)(3.8586)}{\sqrt{2}} = \frac{(110mV)(10)(3.8586)}{\sqrt{2}} = 3.0V \]

When the plates are 30° apart, the peak value of the sine wave is:

\[ V_{4PEAK} = \frac{V_{3PEAK}(10)(3.8586)}{\sqrt{2}} = \frac{(180mV)(10)(3.8586)}{\sqrt{2}} = 4.9V \]
When the plates are 0° apart, the peak value of the sine wave is:

\[ V_{4\text{PEAK}} = \frac{V_{3\text{PEAK}}(10)(3.8586)}{\sqrt{2}} = \frac{(260mV)(10)(3.8586)}{\sqrt{2}} = 7.1V \]

The sine wave output of the filter then goes into an Active Full-Wave Rectifier to double its frequency to enhance the performance of the Active Peak Detector circuit.

6. The Active Full-Wave Rectifier

The schematic diagram of the circuit is in Figure 10 below.

![Schematic Diagram of the Active Full-Wave Rectifier](image)

Figure 10 – The Active Full-Wave Rectifier

To study the behavior of the circuit, we will investigate its response during different half cycles of the input voltage.

During the positive half-cycle, the diode D1 is reverse biased and the diode D2 is forward biased. The equivalent circuit is in Figure 11 on the next page.

The first section of the circuit is an Inverting Amplifier. If we let \( R_A = R_B \), the voltage \( V_X \) is:

\[ V_X = -\frac{R_A}{R_B} V_{IN} = -V_{IN} \]
Figure 11 – The Equivalent Circuit During the Positive Half-Cycle

The second section of the circuit is a Summing Amplifier. The output of this amplifier is:

\[ V_{OUT} = -R_E \left[ \frac{V_X}{R_D} + \frac{V_{IN}}{R_C} \right] = -\frac{R_E}{R_D} \left( -V_{IN} \right) - \frac{R_E}{R_C} \cdot V_{IN} \]

If we let \( R_E = R_C = 2R_D \), then:

\[ V_{OUT} = 2V_{IN} - V_{IN} = V_{IN} \]

Therefore, during the positive half-cycle, the output voltage is equal to the input voltage.

During the negative half-cycle, the diode D\(_1\) is forward biased and the diode D\(_2\) is reversed biased. The equivalent circuit during this half-cycle is in Figure 12 on the next page.

The voltage \( V_X \) in this case is 0V (virtual ground). The second section of the circuit is still a Summing Amplifier. The output of this amplifier is:

\[ V_{OUT} = -R_E \left[ \frac{V_X}{R_B + R_D} + \frac{V_{IN}}{R_C} \right] = -\frac{R_E}{R_C} \cdot V_{IN} = -V_{IN} \]

Therefore, during the negative half-cycle, the output voltage is equal to the inverse of the input voltage.

The input and output waveforms of this circuit are in Figure 13 on the next page.
In our circuit, we use series resistors \( R_{21} - R_{22} \) and \( R_{24} - R_{25} \) to satisfy the resistance requirements as discussed previously. The output frequency of this circuit is 9.64kHz.

7. The Active Peak Detector Circuit

The pulsating DC signal is converted into a DC signal by the Active Peak Detector circuit.

The schematic diagram of the circuit is in Figure 14 on the next page.
In the circuit, if the $R_{27}$ and $C_8$ time constant is a lot larger than the period of the input wave, the wave is “smoothed out” to become an almost DC voltage. This voltage has a small ac ripple.

The time constant of the circuit is:  
$$\tau = (10k\Omega)(10\mu F) = 100ms$$

And the period of the input wave is:  
$$T = \frac{1}{9.64kHz} = 103.7\mu s$$

The typical waveforms of the input and output voltages are in Figure 15 below.

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**Figure 14 – The Active Peak Detector Circuit**

**Figure 15 – The Typical Input and Output Waveforms**
When the output of the Active Full-Wave Rectifier circuit is at its maximum of 7V, the DC current in the Active Peak Detector Circuit is:

\[ I_{DC} = \frac{7.1V}{10k\Omega} = 0.71mA \]

And the peak-to-peak ripple voltage is:

\[ V_{RIPPLE} = \frac{I_{DC}}{fC} = \frac{0.71mA}{(9.64kHz)(10\mu F)} = 7.4mV \]

The above ripple voltage is negligible compared to 7VDC. Therefore, the output voltages of the circuit are 1.1VDC, 3VDC, 4.9VDC, and 7.1VDC when the plates are 90°, 60°, 30°, and 0° apart respectively.

To this point of the design, we have three different voltage levels that indicate the relative position of the top plate to the bottom plate. These voltage levels are:

- When the plates are from 0° to 30° apart, the voltage is from 7.1VDC to 4.9VDC.
- When the plates are from 30° to 60° apart, the voltage is from 4.9VDC to 3VDC.
- When the plates are from 60° to 90° apart, the voltage is from 3VDC to 1.1VDC.

We use different Voltage Comparator and Window Comparator circuits to produce some indications under the following conditions:

- When the plates are from 0° to 30° apart, a green LED is on.
- When the plates are from 30° to 60° apart, a yellow LED is on.
- When the plates are from 60° to 90° apart, a red LED is on.

8. The Voltage Comparator and Window Comparator Circuits

There are two types of comparator circuit that we can use to serve the above purposes. To drive the red LED, we use the following circuit.

The schematic diagram of the first Voltage Comparator is in Figure 16 on the next page.

In this circuit, we utilize the open-loop gain of the 741 operational amplifier (about 100,000). The output of the circuit is:

\[ V_{OUT} = 100,000(V_{REF1} - V_6) \]
Figure 16 – The Voltage Comparator

When \( V_{\text{REF1}} \) is larger than \( V_6 \), the output voltage of the operational amplifier is positively saturated (about 95% of \( V_{\text{CC}} \) or 14.25V). When \( V_{\text{REF1}} \) is less than \( V_6 \), the output of the comparator is negatively saturated (about –14.25V).

Since we wish to have the red LED on until \( V_6 \) reaches 3V, a voltage divider section consisting of \( R_{28} \) and \( R_{29} \) is used to produce this reference voltage \( V_{\text{REF1}} \).

Let \( V_{\text{REF1}} \) be 3V and \( R_{29} \) be 10kΩ, we have:

\[
3V = 15V \cdot \frac{10k\Omega}{R_{28} + 10k\Omega} \Rightarrow R_{28} = \frac{(15V)(10k\Omega)}{3V} - 10k\Omega = 40k\Omega
\]

We use a 39kΩ resistor for \( R_{28} \).

We use the output of the Voltage Comparator as the input of a transistor driver to turn on/off the red LED.

The current driving the red LED is 30mA. The resistor \( R_{31} \) is:

\[
R_{31} = \frac{V_{\text{CC}} - V_{LED}}{I_{LED}} = \frac{15V - 2V}{30mA} = 433.3\Omega
\]

We use a 470Ω resistor for \( R_{31} \).
In order for the transistor to be in switching mode, let the base current $I_B$ to be 3mA ($I_B > 10\% I_{LED}$).

The resistor $R_{30}$ is:

$$R_{30} = \frac{V_{OUT} - V_D - V_{BE}}{I_B} = \frac{14.25V - 0.7V - 0.7V}{3mA} = 4.28k\Omega$$

We use a 3.9kΩ resistor for $R_{30}$.

Thus, when $V_6$ is less than 3V, the output voltage of the Voltage Comparator is 14.25V driving the base of the transistor to put it in saturation to turn on the red LED. When $V_6$ is more than 3V, the output of the Voltage Comparator is –14.25V. The diode $D_3$ is reverse biased. The transistor is in cut off turning off the red LED.

We can use similar approach to drive the green LED. The circuit is in Figure 17 below.

![Figure 17 – Another Voltage Comparator](image)

The output voltage of the operational amplifier is:

$$V_{OUT} = 100,000(V_6 - V_{REF2})$$
In the circuit, a second reference voltage $V_{REF2}$ is:

$$V_{REF2} = (15V) \frac{12k\Omega}{22k\Omega + 12k\Omega} = 5.3V$$

Thus, when the input voltage $V_6$ is less than $V_{REF2}$ of 5.3V, the output of the Voltage Comparator is negatively saturated turning off the green LED.

When the input voltage $V_6$ is more than $V_{REF2}$ of 5.3V, the output of the Voltage Comparator is positively saturated turning on the green LED.

We can combine the above ideas to create a Window Comparator circuit to drive the yellow LED. The schematic diagram of this circuit is in Figure 18 below. In the circuit, the reference voltages $V_{REF1}$ and $V_{REF2}$ discussed previously are use as the lower limit and upper limit voltages of the comparator.

![Figure 18 – The Window Comparator](image)

When the input voltage $V_6$ is more than $V_{REF2}$, the output of the top comparator is positively saturated. This voltage drives the transistor into saturation resulting in the yellow LED being off.

When the input voltage $V_6$ is less than $V_{REF1}$, the output of the bottom comparator is positively saturated. This voltage drives the transistor into saturation resulting in the yellow LED being off.
When the input voltage $V_6$ is between $V_{REF1}$ and $V_{REF2}$, the outputs of both top comparators are negatively saturated. This voltage drives the transistor into cut-off resulting in the yellow LED being on.

**C. Conclusion**

The project produces indicators for the relative position between the top plate and the bottom plate of the variable capacitor. A red LED shows that the two plates are between $60^\circ$ to $90^\circ$ apart. A yellow LED indicates that the two plates are between $30^\circ$ to $60^\circ$ apart and a green LED indicates that the two plates are between $30^\circ$ to $0^\circ$ apart.

The project consists of different analog circuits that the students have learned during the first three semesters in the Electrical Engineering Technology Program of Purdue University. This design gives the students an opportunity to put into practice the theories and applications they possess. It also enhances their troubleshooting skills.

**Bibliography**


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