Investigation into Differentiators, Integrators, Timers, and Buzzers

Natalia Tabja[1]

[1] *Department of Physics, University of Toronto*

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This report investigates the behavior of differentiator and integrator circuits using operational amplifiers, as well as the performance of 555 timer-based circuits in various configurations. The results from experimental measurements are compared against theoretical expectations. Oscilloscope screen captures are analyzed to understand waveform transformations. Additionally, a push-button buzzer circuit is tested, and the effect of varying components on circuit behavior is explored.

INTRODUCTION

Differentiators and integrators are fundamental circuits in signal processing. The differentiator emphasizes high-frequency components, while the integrator acts as a low-pass filter. The 555 timer is widely used in pulse generation and waveform shaping. This lab explores these circuits and their response to various inputs, including ramp and square waves. The impact of component changes on frequency and duty cycle is also examined.

DIFFERENTIATORS

R-1: Oscilloscope Output for Differentiator Circuit

To analyze the behavior of the differentiator circuit, we examined its output when subjected to different input frequencies. The oscilloscope captures below compare the experimental output to the expected theoretical behavior.

For an input signal of 50Hz with 1V_{pp} amplitude and 0V offset, the expected differentiator output should be a square wave with the same frequency. Since differentiation calculates the rate of change, the output voltage is proportional to the derivative of the input. A ramp function has a constant slope, meaning the derivative results in a constant voltage level, forming a square wave.

The expected amplitude can be determined as:

$$V_{\text{out}}(t) = -RC\frac{dV_{\text{in}}}{dt} \tag{1}$$

where R and C are the resistance and capacitance in the differentiator circuit, respectively. Given that the input ramp waveform is characterized by:

$$\frac{dV_{\text{in}}}{dt} = \frac{A}{T/2} = \frac{1V}{10ms} = 100\text{ V/s} \tag{2}$$

with $A = 1V$ and $T = 20$ ms for a 50 Hz signal, the peak output voltage depends on the chosen RC values.

For example, in the case of a $1\mu F$ capacitor and $R = 1k\Omega$, the expected output amplitude is:

$$V_{\text{out}} = -(1k\Omega)(1\mu F)(100\text{ V/s}) = -0.1V \tag{3}$$

which is within reasonable limits given typical op-amp constraints.

The oscilloscope capture confirms the theoretical expectations for the 50 Hz signal:

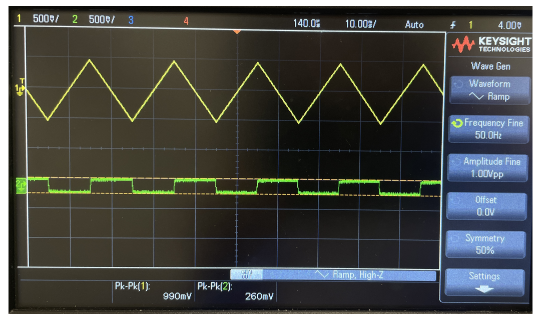

FIG. 1. Oscilloscope output for 50Hz input frequency. The expected square wave behavior is observed.

For an input signal of 1kHz with 1V_{pp} amplitude and 0V offset, the output did not match the expected waveform observed in the Falstad simulation. While the output is close to a square wave, the slightly slanted or rounded tops/bottoms of the waveform suggest capacitor charging effects.

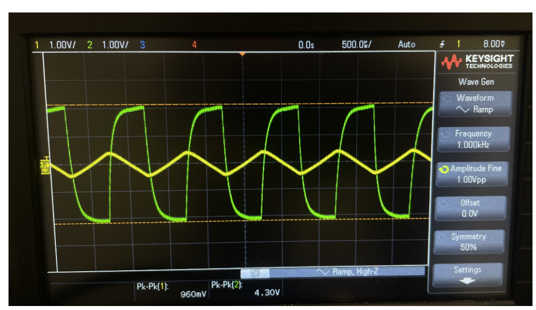

FIG. 2. Oscilloscope output for 1kHz input frequency. The upticks are affected by capacitor charging.

R-2: Effect of a 100nF Parallel Capacitor

Adding a 100nF capacitor in parallel with the 1k resistor degraded the circuit's performance, increasing distortions and reducing sharp transitions in the output waveform. The oscilloscope image shown below corresponds to testing conducted at 1kHz, as suggested.

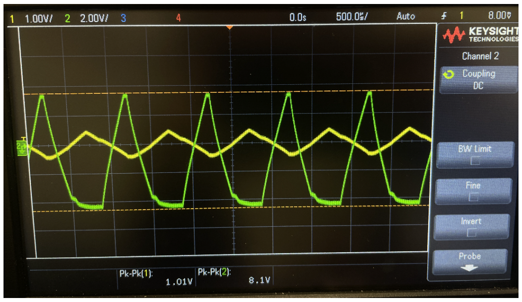

FIG. 3. Oscilloscope output after adding a 100nF capacitor in parallel with the 1k resistor. The waveform distortion increased.

The addition of the capacitor in parallel with the resistor reduced the circuit's ability to respond to rapid changes in voltage, effectively suppressing the differentiation effect. Instead of producing a sharp square wave as expected for a differentiator, the output became more triangular. This suggests that the capacitor altered the frequency response of the circuit, acting as a low-pass filter that attenuated the higher-frequency components necessary for sharp transitions.

INTEGRATORS

R-3: Integrator Output Analysis

To analyze the performance of the integrator circuit, we applied a square wave input with a 1kHz frequency, 1V$_{pp}$ amplitude, and 0V offset.

Given the theoretical behavior of an ideal integrator, the expected output should be a triangular waveform. This is because the integral of a square wave is a linearly increasing and decreasing function.

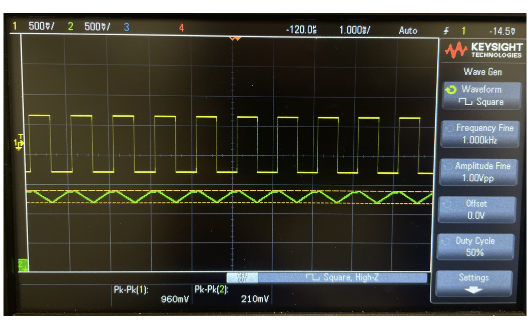

FIG. 4. Oscilloscope output for 1kHz square wave input. The output correctly integrates the input, producing a triangular waveform.

The oscilloscope capture in Fig. 4 confirms this, showing that the circuit indeed produces a triangular waveform. However, minor deviations from an ideal triangular wave can be observed, particularly at the peaks, which seem slightly flattened.

This is likely explained by the fact that the LF356 op-amp has a finite slew rate of 12 V/μs[3], as opposed to an ideal op-amp with infinite slew rate. This make the instantaneous transition from a positive to negative slope impossible; rather, it happens over some finite period of time, causing the peaks of the triangles to be slightly flat.

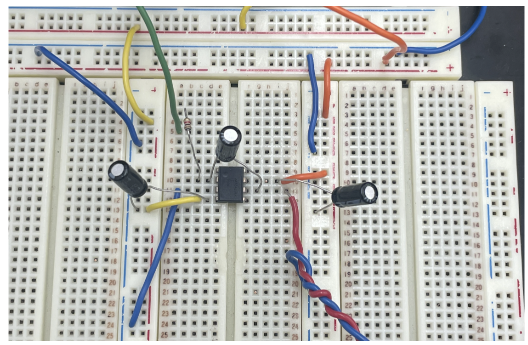

FIG. 5. Breadboard implementation of the integrator circuit.

R-4: Evaluating DC Offset Mitigation Strategies

We tested several modifications to reduce DC offset, including grounding the offset at the input/output, adding DC feedback, and blocking DC at the output. However, none of these changes resulted in a measurable improvement in the output. This suggests that the original circuit was already functioning within acceptable limits, likely due to the LF356 op-amp's low offset voltage and bias currents. The TA confirmed that no significant improvement was expected, indicating that further modifications were unnecessary for our setup.

TIMER

R-5: Output Capture

A 555 timer circuit was built following figure 6-5 of the NE555P Spec Sheet [4], using $R_A = 330k$, $R_B = 100k$, and $C = 47nF$, leaving R_L out. Its output waveform was observed on an oscilloscope.

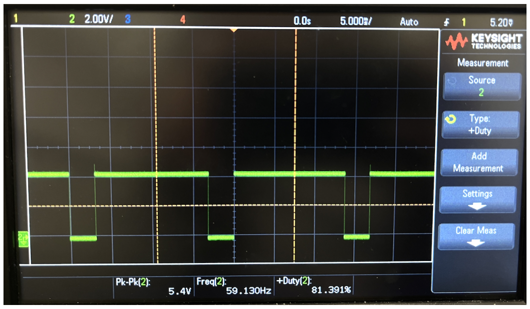

FIG. 6. Oscilloscope capture of the 555 timer circuit output waveform. The measured frequency and duty cycle closely match the expected values based on the NE555P timer equations

TABLE I. Effect of component variations on timer frequency and duty cycle, incorporating measurement uncertainties. f_E and D_E correspond to the expected (theoretical) frequencies and duty cycles, respectively. The uncertainties in resistance, capacitance, and frequency were calculated based on the Keysight 34461A Digital Multimeter and Keysight InfiniiVision 1000 X-Series Oscilloscope specification sheets [1, 2].

R_A (kΩ)	R_B (kΩ)	C (nF)	f_E (Hz)	f (Hz)	D_E (%)	D (%)
486.79 ± 0.07	98.72 ± 0.01	46.9 ± 0.3	57.8	59.0 ± 8	81.1	81.3 ± 0.5
146.4 ± 0.03	98.72 ± 0.01	46.9 ± 0.3	44.7	45.2 ± 6	85.1	88.8 ± 0.4
326.19 ± 0.05	146.4 ± 0.03	46.9 ± 0.3	50.0	49.7 ± 7	76.2	76.4 ± 0.4
486.79 ± 0.07	98.72 ± 0.01	100 ± 0.3	27.0	28.5 ± 4	81.1	81.4 ± 0.5
135.0 ± 0.01	98.72 ± 0.01	46.9 ± 0.3	87.5	78.6 ± 10	70.1	74.6 ± 0.5

R-6: FREQUENCY AND DUTY CYCLE ADJUSTMENTS

Different resistor and capacitor values were tested to observe their impact on the output frequency and duty cycle of the 555 timer circuit. The theoretical expressions for these parameters are given by the NE555P specifications sheet [1]:

$$f \approx \frac{1.44}{(R_A + 2R_B)C} \tag{4}$$

$$D = \frac{R_A + R_B}{R_A + 2R_B} \times 100\% \tag{5}$$

where:

- R_A and R_B are the resistances in kΩ,
- C is the capacitance in nF,
- f is the output frequency in Hz, and
- D is the duty cycle in percentage.

To verify these equations, different values of R_A, R_B, and C were used in the circuit, and the corresponding expected and measured values for the frequency and duty cycle were recorded in Table I.

Discussion of Results

The recorded values in Table I are consistent with the theoretical relationships described in Equations 4 and 5. The behavior of the circuit under different conditions is analyzed below:

Reference Point For $R_A = 330k\Omega$, $R_B = 100k\Omega$, and $C = 47nF$, the circuit operated as expected, producing a frequency of 59.0 ± 8 Hz, closely matching the theoretical value of 57.8 Hz. Similarly, the measured duty cycle of 81.3% aligns well with the expected 81.1%.

Increasing R_A, Keeping R_B Constant Increasing R_A to $470k\Omega$ while keeping R_B at $100k\Omega$ should reduce the frequency, as predicted by Equation 4. The expected frequency dropped to 44.7 Hz, and the measured value of 45.2 ± 6 Hz follows this trend. The duty cycle was expected to increase to 85.1%, and the measured 88.8% confirms this.

Increasing R_B, Keeping R_A Constant When R_B was increased to $150k\Omega$, the frequency was expected to drop, which was observed in the measured value of 49.7 ± 7 Hz compared to the expected 50.0 Hz. The duty cycle also decreased as predicted, with the theoretical 76.2% compared to the measured 76.4%.

Increasing C, Keeping R_A and R_B Constant Increasing the capacitance from $47nF$ to $100nF$ should decrease the frequency significantly due to its inverse proportionality in Equation 4. The expected frequency of 27.0 Hz was closely matched by the measured value of 28.5 ± 4 Hz. The duty cycle, which is independent of capacitance, remained nearly unchanged at 81.4%, consistent with the theoretical 81.1%.

Decreasing R_A, Keeping R_B Constant Lowering R_A to $135k\Omega$ should increase the frequency. The measured value of 78.6 ± 10 Hz is slightly lower than the expected 87.5 Hz, which may be attributed to component tolerances. The expected decrease in duty cycle to 70.1% is reflected in the measured value of 74.6%.

Overall, the experimental results show a strong agreement with the predictions based on equations 4 and 5, with minor deviations likely due to component tolerances and measurement uncertainties. One could do more test cases, such as decreasing the capacitance (which should lead to a higher frequency), but we believe the test cases done provide reasonable assurance that the circuit is working as expected.

BUZZER

R-7: RESISTOR CHOICE RATIONALE

We replaced R_A instead of R_B because changing R_A allows for a wider frequency range and improves the duty cycle, making it closer to 50% for a cleaner buzzer sound. According to the NE555 datasheet [4], the capacitor in an astable 555 timer circuit charges through both R_A and R_B but discharges only through R_B. This means that R_A directly influences the high time (t_H) of the waveform, while R_B affects both the charge and discharge times.

Since the duty cycle is given by Equation 5, adjusting R_A only increases the charge time while keeping the discharge time unchanged. This provides a more controlled way to tune the duty cycle toward 50%, which is desirable for a clearer and more balanced buzzer sound. On the other hand, modifying R_B alone would affect both charge and discharge times, making it harder to control the duty cycle precisely.

By increasing R_A, we achieved a duty cycle closer to 50%, optimizing the buzzer's performance without significantly distorting the waveform.

R-8: Push-Button Buzzer Demonstration

A short video was recorded demonstrating the buzzer circuit operation, and has been uploaded to Quercus.

CONCLUSION

This lab explored differentiator and integrator circuits and their responses to various input signals. A 555 timer was used to generate pulses, and its frequency and duty cycle were analyzed. Finally, a buzzer circuit was tested, demonstrating pitch variations through resistance adjustments. The experimental results were consistent with theoretical expectations, with minor deviations due to real-world component imperfections.

Acknowledgements

These experiments were performed in collaboration with Sanai Nezafat.

[1] Keysight Technologies, *InfiniiVision 1000 X-Series Oscilloscopes Data Sheet*, `https://www.keysight.com/ca/en/assets/7018-06411/data-sheets/5992-3484.pdf`, 2019. [Accessed: Mar. 13, 2025].

[2] Keysight Technologies, "34461A Digital Multimeter Datasheet," `https://www.keysight.com/ca/en/assets/7018-06411/data-sheets/34461A.pdf`, 2025. [Accessed: Mar. 13, 2025].

[3] Texas Instruments, "LF356 JFET-Input Operational Amplifier," `https://www.ti.com/product/LF356`.

[4] Texas Instruments, "LM555 Timer Datasheet," `https://www.ti.com/lit/ds/symlink/ne555.pdf`.