Analysis and Implementation of Single-Supply Comparators and Relaxation Oscillators

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***Abstract*—The study focuses on constructing, testing, and analyzing single-supply comparators and relaxation oscillators. Two types of inverting voltage comparators are examined: a standard comparator with a half-supply trigger level and a Schmitt trigger circuit. Additionally, a relaxation oscillator combining an RC low-pass circuit and an inverting hysteretic comparator is explored. Utilizing the TLC3702 MOS Comparator IC and various Keysight instruments, the experiments aim to enhance the understanding of electrical concepts such as hysteresis and duty cycles.**

The experiments involve assembling comparator circuits and testing them with signal generators and oscilloscopes to study trigger level behaviors and output waveforms. The relaxation oscillator's investigation emphasizes the analysis of square-wave oscillation, focusing on the relationship between the circuit's time constant and the comparator's trigger levels. Insightful observations are made regarding the output's switching response to input variations, revealing intricate details of circuit operations.

Methodologies, experimental results, and in-depth analyses demonstrate the practical application and interpretation of electrical circuit theory. The study offers a comprehensive understanding of the link between theoretical principles and their practical implementation in electrical engineering, enhancing knowledge and skills in circuit design and analysis.

***Index Terms*—Voltage Comparator, Hysteresis, Schmitt Trigger, Relaxation Oscillator, Duty Cycle, Integrated Circuit, Electrical Circuit Analysis.**

I. Introduction

Exploring the intricacies of electronic circuits is a foundational aspect of electrical engineering, with particular emphasis on their practical applications and theoretical underpinnings. The focus of this study is on single-supply comparators and relaxation oscillators, examining their construction, functionality, and significance in the broader context of circuit design. Central to this exploration are two types of inverting voltage comparators: the standard comparator with a half-supply trigger level and the Schmitt trigger, or hysteretic comparator. Additionally, the design and analysis of a relaxation oscillator, an essential component in various electronic systems, form a crucial part of the investigation.

The initial phase involved assembling comparator circuits using the TLC3702 MOS Comparator IC and other essential components, with a key emphasis on achieving accurate and stable circuit operation. Understanding the comparators' response to input signals and their switching behaviors at different voltage levels was crucial, given their widespread application in voltage level detection, signal conditioning, and noise filtration in electronic devices.

Subsequently, attention turned to the relaxation oscillator. This phase required constructing a circuit comprising an RC low-pass filter and an inverting hysteretic comparator, delving into how these components interact to influence the frequency and duty cycle of the oscillator's output. Such insights are particularly valuable in applications demanding precise timing and signal generation, highlighting the oscillator's versatility.

Throughout the study, practical experimentation complemented theoretical analysis, showcasing the relationship between hands-on experience and academic knowledge in electrical engineering. The outcomes not only demonstrated the successful implementation of these circuits but also deepened the understanding of their operational principles, potential modifications, and diverse applications.

Consequently, a detailed account of the methodologies, experimental setups, observations, and analytical insights forms the crux of the study. These findings contribute to a nuanced understanding of electronic circuits, especially comparators and comparator based circuits.

II. Background and Preliminaries

A. Voltage Comparators: Detailed Fundamentals

Voltage comparators are fundamental components in electronic circuits, pivotal in making binary decisions based on voltage levels. These devices compare an input voltage against a reference level and output a high or low signal based on the comparison. This simple mechanism is crucial in applications ranging from automated industrial processes to everyday consumer electronics.

1) Historical Development and Technological Evolution: Initially, comparators were built using discrete components like diodes and transistors, which later evolved into operational amplifiers configured in an open-loop mode. The advent of digital technology saw the integration of comparators into sophisticated integrated circuits (ICs), enhancing their precision and efficiency. This evolution transformed comparators into versatile tools in digital electronics, playing a significant role in modern applications like automotive sensor systems, where precise voltage comparison determines safety-critical decisions.

2) Design Considerations and Parameters: Designing a comparator circuit involves considerations like:

- **Input Offset Voltage:** Crucial for applications requiring high precision, such as medical monitoring devices, where small voltage differences can be critical.
- **Response Time and Speed:** Essential in fast-responding systems, like electronic speed controllers in drones, where rapid voltage comparisons are necessary for stability and control.
- **Power Consumption:** Key in portable electronics, like smartphones, ensuring energy efficiency and longer battery life.
- **Noise Immunity:** Vital in industrial environments, where electrical noise can interfere with the accurate reading of sensor data in machinery control systems.

3) Types of Comparators and Their Uses:

- **Standard Comparator:** Common in applications like solar panel voltage monitoring, where they ensure optimal energy harnessing by comparing the output voltage with a predefined threshold.
- **Hysteretic Comparator (Schmitt Trigger):** Used in digital signal processing to clean up noisy signals, such as in audio interfaces, where they convert analog signals into digital form for processing and recording.

B. Relaxation Oscillators: In-Depth Exploration

Relaxation oscillators generate periodic waveforms, crucial in systems requiring consistent timing signals. They function by charging and discharging a capacitor through a resistor, creating a waveform that toggles between two voltage levels. This simple yet effective mechanism is foundational in devices like electronic beepers in alarm clocks and flashing lights in safety signals.

1) Component Selection and Circuit Dynamics:

- **Capacitor and Resistor Interaction:** Critical in determining the frequency of blinking in LED traffic warning signs, where precise timing ensures effective warning signals.
- **Comparator Integration:** Enhances the oscillator's precision, vital in electronic musical instruments like synthesizers, where they generate audio tones with specific frequencies.

2) Design Implications and Applications:

- **Noise and Stability:** In communication devices, such as radio transmitters, ensuring oscillator stability against environmental interference is key for clear signal transmission.
- **Frequency Tuning:** Adjustable frequency is crucial in calibration equipment used in laboratories to test and validate the performance of various electronic devices.

C. Comprehensive Applications and Engineering Significance

Voltage comparators and relaxation oscillators have extensive applications, influencing numerous aspects of technology. They are instrumental in precision tools and systems, from household appliances to complex industrial automation and aerospace engineering.

1) Broader Engineering and Design Implications: For engineers and designers, mastering these components is essential. Their applications in designing efficient, reliable, and precise electronic systems are evident in sectors like renewable energy, where comparators help in maximizing solar panel output, and in space exploration, where oscillators ensure the timing accuracy of satellite communication systems.

III. DESIGN

A. Design of Comparator with a Fixed $\frac{1}{2}$-Supply Trigger Level

Primary Objective:

- Assemble and validate a single-supply inverting voltage comparator using the TLC3702 chip with a V_{CC} of 10V.

Sub-Objectives:

- Circuit Assembly: Assemble as per Figure 1, ensuring equal values for resistors R1 and R2.
- Validation of Circuit Functionality: Use an oscilloscope to validate the trigger level at $\frac{1}{2}$ of V_{CC}.
- Safety and Precaution: Proper termination of the unused comparator.

Anticipated Outcomes:

- Successful assembly and validation.
- Clear oscilloscope reading of the trigger level.

Applications: Useful in voltage level detection applications like battery level indicators and switching power regulators.

1) Electrical Components and Equipment:

- Two 200 kΩ Resistors
- TLC3702 MOS Comparator IC
- DC Power Supply, Function Generator, Oscilloscope, Digital Multimeter
- Breadboard and various wiring accessories

2) Circuit Assembly and Validation:

- Assembly as per Figure 1, with emphasis on accurate connections and safety.
- Utilization of function generator and power supply to generate test waveforms.
- Oscilloscope and multimeter used for measurements and validation.

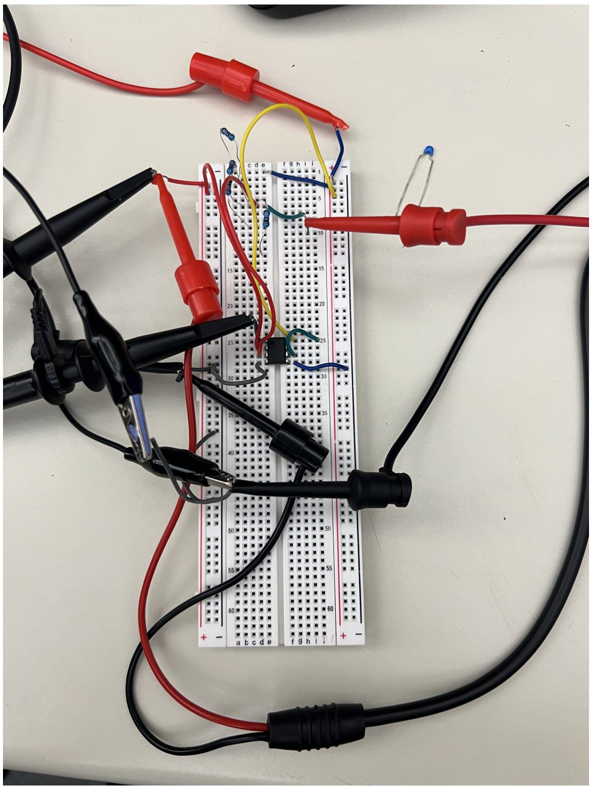

Fig. 1: Comparator with a fixed $\frac{1}{2}$-supply trigger level

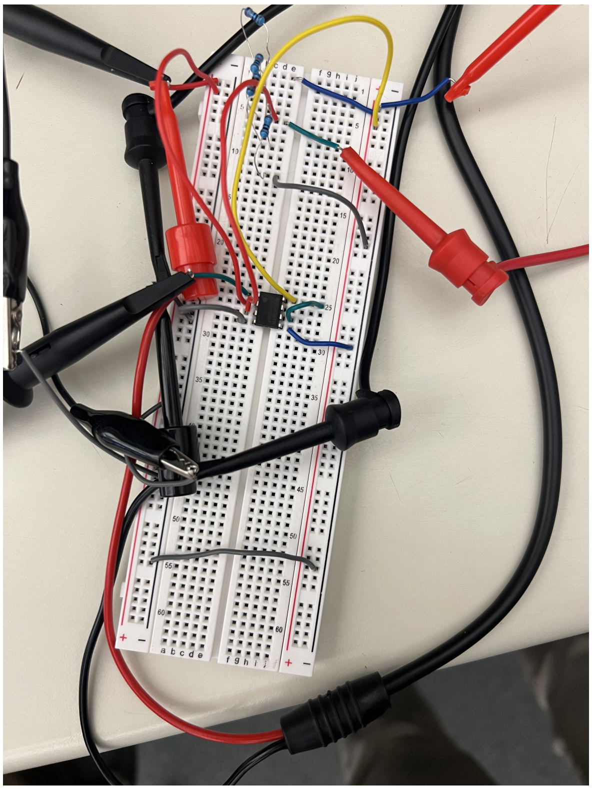

Fig. 2: Hysteretic Comparator

3) Design Considerations:

- **Reference Voltage:** Carefully selecting the reference voltage determines the switching point of the comparator. In applications requiring precision, the reference voltage must be stable and free from noise.
- **Input Bias Current:** Comparators often have minute input bias currents. These currents can generate voltage drops across input resistors, potentially affecting accuracy.
- **Propagation Delay:** The time taken for the comparator to switch its output after an input threshold is crossed should be considered, especially in high-frequency applications.
- **Power Supply:** The power supply voltage defines the output swing of the com- parator. It's vital to ensure that the supply voltage is compatible with subsequent stages.
- **Noise Immunity:** Without hysteresis, the comparator can be susceptible to noise, causing unwanted output transitions. Filtering or shielding techniques might be required to reduce the influence of external interference.

B. Design of Hysteretic Comparator

Primary Objective:

- Construct and validate a hysteretic comparator for different voltage level switching.

Sub-Objectives:

- Circuit Modification and Verification: Modification as per Figure 2 and functionality validation.
- Data Acquisition: Scope captures to visualize switching at two different voltage levels.

Anticipated Outcomes: Functional comparator with two distinct trigger levels.

Applications: Utilized in sensor signal conditioning, signal amplifiers, and communication systems.

1) Electrical Components and Equipment: Similar to the previous section, with the addition of resistor.

2) Setup and Validation:

- Circuit modification as per Figure 2, with a focus on safety.
- Use of oscilloscope for validation and data acquisition.

3) Design Considerations:

- **Feedback Resistor (R3)**: Influences the hysteresis window width.

C. Design of Relaxation Oscillator

Primary Objective:

- Construct a relaxation oscillator to analyze square-wave oscillation.

Sub-Objectives:

- Circuit Construction and Analysis: As per Figure 3, focusing on RC network and inverting hysteretic comparator.
- Oscillation Analysis: Measure frequency and average value of square-wave.

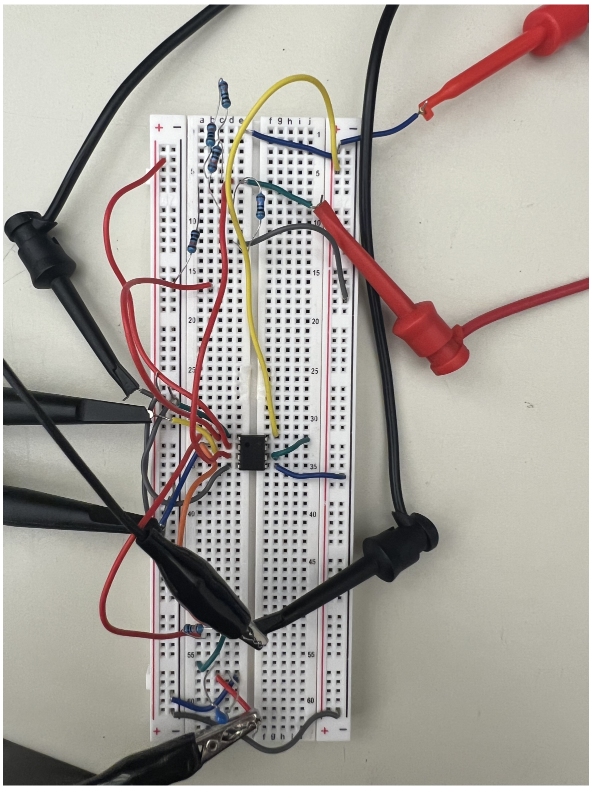

Fig. 3: Relaxation Oscillator

- Duty Cycle Analysis: Investigate impact on oscillation frequency and duty cycle.

Anticipated Outcomes: Continuous square wave generation with frequency and duty cycle dependent on component values.

Applications: Used in clock pulses, light flashers, tone generation in alarms, and signal conversion.

1) Electrical Components and Equipment:

- Additional 100 kΩ resistors and 1nF capacitor.
- Similar equipment as previously mentioned.

2) Design Considerations for Relaxation Oscillator:

- **RC Time Constant:** The choice of resistor (R) and capacitor (C) values in the RC network is crucial. The RC time constant ($\tau = RC$) determines the frequency of oscillation. The values must be chosen to ensure the oscillator operates within the desired frequency range for your application.
- **Power Supply Considerations:** The operating voltage range of the circuit components, particularly the comparator, must be compatible with the available power supply. This ensures reliable operation and avoids component damage.
- **Load Capacitance and Drive Ability:** The oscillator's output load can affect its performance. Ensure that the comparator can drive the expected load without significant distortion or frequency shift.

IV. Verification and Execution

A. Setup and Verification of Comparator with a Fixed $\frac{1}{2}$-Supply Trigger Level

1) Circuit Assembly and Initial Precautions: Prior to initiating the experiment, the TLC3702 comparator chip and resistors were visually inspected to ensure no physical damage or abnormalities were present. The circuit was assembled as per Figure 1, with special attention given to securely placing the IC and ensuring all connections were accurate and firm. The unused comparator was terminated properly to prevent potential damage, following the guidelines provided.

2) Signal Generation and Power Verification: The function generator and DC power supply were activated and configured to provide a triangular test waveform that sweeps from 0V to 10V and a stable 10V supply, respectively. The generated test signal and supply voltage were verified using an oscilloscope and a digital multimeter, ensuring alignment with the specified values.

3) Measurement and Data Recording: Upon ensuring stable and accurate signal generation and power supply, the circuit was powered, and measurements were conducted. The correctness of the positive "+" terminal of the comparator was verified using the digital multimeter. Oscilloscope captures were taken, showing the input triangular wave and the resulting output square wave to validate the functionality of the assembled circuit.

B. Setup and Verification of Hysteretic Comparator

1) Setup Error: While setting up the next circuit I decided to use the sourcemeter instead of the power supply which ended up frying the comparator and melting a portion of the breadboard as the sourcemeter pushed current through. When I used the correct DC source, I saw that the circuit was taking 0A, so I know that circuit did not need any current which is most likely why the comparator was fried when current was forced in. I acquired a second comparator, moved the circuit down the breadboard to not use the fried nodes and then correctly wired the circuit and the circuit worked as intended.

2) Circuit Modification and Safety Measures: Transitioning from part A, resistor $R3$ was added to the circuit without disconnecting the power supply and signal generator.

3) Validation and Data Acquisition: Upon modifying the circuit, the power supply and signal generator were re-enabled. Oscilloscope captures were taken, showcasing the input triangular wave and the output square wave, alongside the input wave and positive "+" terminal of the comparator.

C. Setup and Verification of Relaxation Oscillator

1) Circuit Construction and Activation: Building upon part B, the signal generator was disabled and disconnected, and the RC network was introduced, closing the loop as shown in Figure 4. The 10V power supply was enabled, prompting the circuit to produce a square-wave oscillation autonomously.

2) Observation and Data Acquisition: Two sets of oscilloscope captures were collected, showcasing the voltage across the capacitor & output (square wave) and voltage across the capacitor & positive "+" terminal of the comparator. Additionally, the oscillation frequency and the average value of the square-wave were measured and recorded using the oscilloscope.

V. Measurements

TABLE I: Capacitor and Resistors

Cap. (nF)	**R1 (kΩ)**	**R2 (kΩ)**	**R3 (kΩ)**	**R4 (kΩ)**	**R5 (kΩ)**	**R6 (kΩ)**
1.05	97.5	98.3	99.7	100.2	99.3	100

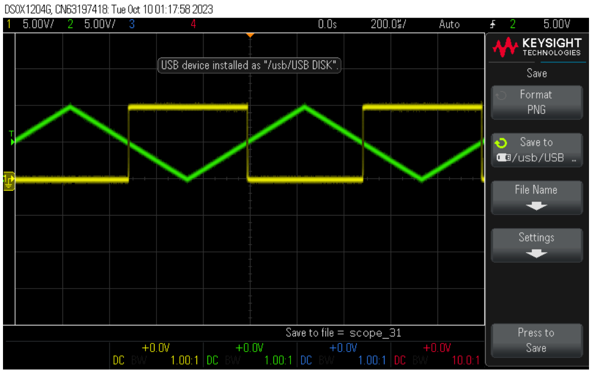

Fig. 4: Fixed ½-supply trigger level

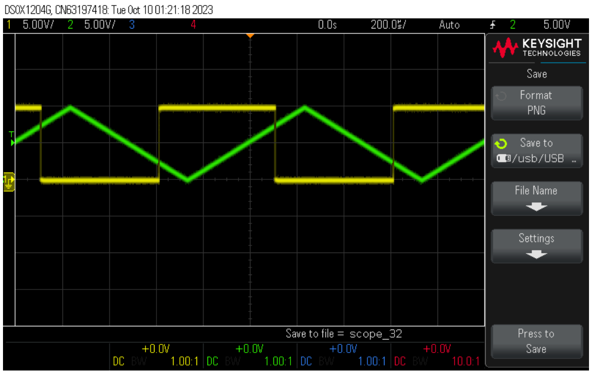

Fig. 5: Hysteretic Comparator modified trigger level

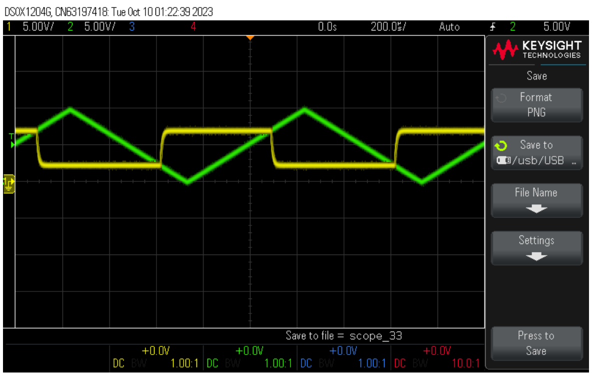

Fig. 6: Input (triangular) wave & positive "+" terminal of the comparator.

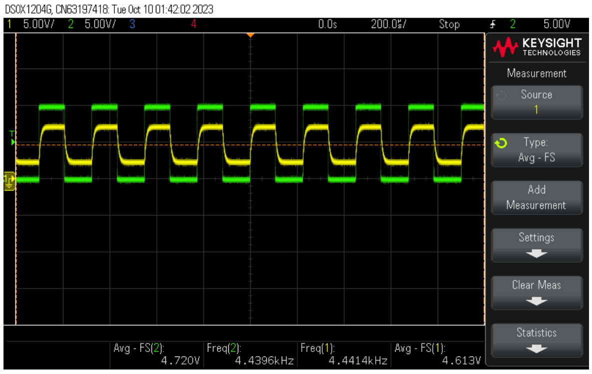

Fig. 7: Voltage across the capacitor & output (square wave)

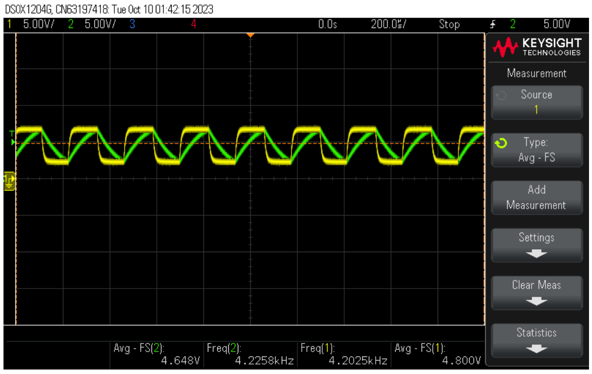

Fig. 8: Voltage across the capacitor & positive "+" terminal of the comparator

VI. Analysis

A. Comparator with 1/2-Supply Trigger Level

1) Operation of Comparator: Comparators function by comparing two input voltages and outputting a binary signal. The operation is straightforward: when the non-inverting input is greater than the inverting input, the output is high, and when it's lower, the output is low. This binary nature makes comparators essential in digital electronics for making voltage level decisions.

2) Input (Triangular Wave): A triangular wave ranging from 0V to approximately 10V was used as the input. This wave form is particularly useful for testing comparators as it linearly ramps up and down, allowing us to observe the comparator's response at various points along the voltage range.

3) Fixed 1/2-Supply Trigger Level: For a supply voltage of 10V, the mid-point or 1/2-supply level is 5V. As shown in Fig 4, this voltage level serves as the threshold for the comparator, acting as the reference point against which the input voltage is compared.

4) Output (Square Wave):

- The comparator's output transitions to high (typically the supply voltage) when the triangular wave's amplitude exceeds 5V.
- Conversely, the output switches to low (typically ground level) when the amplitude falls below 5V.

- This results in a square wave output, aligning its transition edges with the input wave's crossing of the 5V threshold. This is a key behavior in digital signal processing where sharp, clean transitions are essential.

5) Hysteresis and Noise Susceptibility in Comparators: Hysteresis is a significant factor in comparator design, enhancing stability, especially in noisy environments. Without hysteresis, a comparator can be too sensitive to minor voltage fluctuations, often found in real-world signals, leading to multiple unwanted toggling of the output.

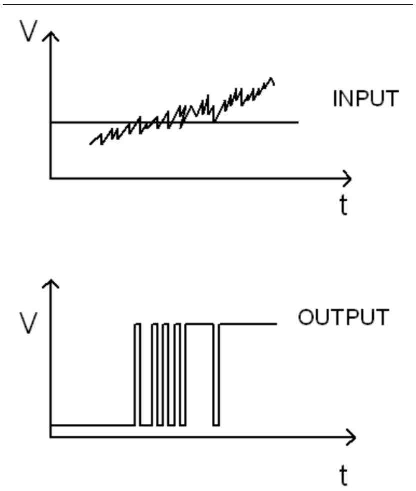

Fig. 9: Ideal vs. Noisy Input Signals

Figure 9 demonstrates the effect of noise on a comparator's operation. It shows how a noisy signal can cause the input voltage to fluctuate around the threshold, leading to erratic output behavior. This is where hysteresis proves beneficial, as it introduces a buffer zone around the threshold, preventing the output from toggling due to minor variations in the input signal.

B. Hysteretic Comparator

1) Hysteretic Comparator Behavior: The hysteretic comparator, characterized by its two distinct switching thresholds, introduces a hysteresis loop into the comparator's operation. This behavior is crucial for applications where noise immunity is vital.

2) Hysteresis in the Scope Capture: The oscilloscope images provide evidence of the hysteresis effect in action:

- The square wave output transitions from low to high at a higher input voltage point, representing the upper threshold of the hysteresis loop.
- Conversely, the output transitions from high to low at a lower input voltage point, indicating the lower threshold of the hysteresis loop.
- These two distinct thresholds form a hysteresis window, enhancing the comparator's tolerance to noise and preventing false triggering.

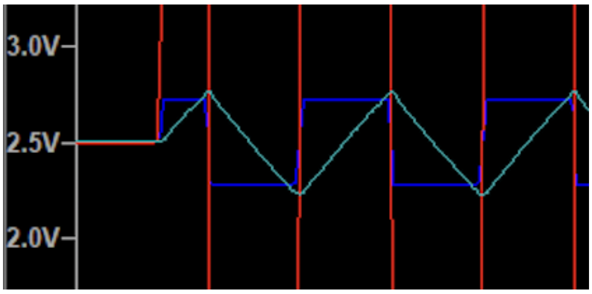

Fig. 10: Hysteretic window with Feedback Resistor being 5x (550kΩ)

3) Role of the 100kΩ Resistor (R3): The 100kΩ resistor (R3) plays a pivotal role in establishing the hysteresis characteristics:

- R3 was added to the circuit to create positive feedback, which is essential for generating the hysteresis effect.
- The value of R3 is directly proportional to the width of the hysteresis window. In this case, a 100kΩ resistor sets the window between 1/4Vcc and 3/4Vcc, providing a substantial buffer against noise as shown in Figure 5.
- This resistor choice is a critical design decision, balancing the need for noise immunity with the comparator's responsiveness. A higher resistor value results in a tigheter window as shown in Figure 10.

C. Relaxation Oscillator

1) Figure 7: Nature of the Waveforms: The first oscilloscope capture illustrates the characteristic waveforms of the relaxation oscillator:

- The sinusoidal waveform, visible in the capture, indicates the charging and discharging cycle of the capacitor in the oscillator circuit.
- The superimposed square waveform represents the comparator's output, which toggles in response to the capacitor's voltage reaching specific thresholds.

2) Voltage Levels: The capture shows distinct voltage levels corresponding to the oscillator's operation:

- The square waveform toggles between 0V and 5V, delineating the on/off states of the comparator.
- The sinusoidal waveform oscillates around specific voltage levels, set by the hysteresis window, which in this case are around 1/4Vcc and 3/4Vcc.

3) Figure 8: Nature of the Waveforms: The second capture provides additional insights:

- It displays the phase relationship between the voltage across the capacitor and the voltage at the comparator's positive terminal.
- This phase difference is indicative of the time delay introduced by the RC network and the comparator's response time, crucial for understanding the oscillator's timing characteristics.

4) Voltage Levels: In the second capture, the observed voltage levels further validate the hysteresis window's role in the oscillator's operation:

- Both the capacitor's voltage and the comparator's positive terminal voltage oscillate within the hysteresis window, reaffirming the stability and predictability of the oscillator's operation.

VII. Equations

A. Inverting Voltage Comparator

For the inverting voltage comparator with a half-supply trigger level, the trigger level (V_{trigger}) can be calculated as follows, assuming equal resistor values ($R1 = R2$):

$$V_{\text{trigger}} = \frac{1}{2}V_{CC} \tag{1}$$

where V_{CC} is the supply voltage.

B. Hysteretic Comparator

In the hysteretic comparator, also known as a Schmitt trigger, the trigger levels are defined by the resistor values. For $R1 = R2 = R3$, the upper ($V_{\text{TH+}}$) and lower ($V_{\text{TH-}}$) trigger levels are given by:

$$V_{\text{TH+}} = \frac{2}{3}V_{CC} \tag{2}$$

$$V_{\text{TH-}} = \frac{1}{3}V_{CC} \tag{3}$$

These equations assume an ideal comparator that can pull its output to either V_{CC} or GND.

C. Hysteretic Comparator with Unequal Resistances

In cases where $R3$ does not equal $R1$ or $R2$, particularly when $R3 = 5 \times R1$ (assuming $R1 = R2$), the trigger levels are affected. The upper ($V_{\text{TH+}}$) and lower ($V_{\text{TH-}}$) trigger levels in this scenario can be calculated as follows:

1) Upper Trigger Level (V_{TH+}): When the output is high (close to V_{CC}):

$$V_{\text{TH+}} = \frac{R1}{R1 + \frac{R3\|R2}{R3+R2}}V_{CC} \tag{4}$$

where $R3 \parallel R2$ denotes the parallel combination of $R3$ and $R2$.

2) Lower Trigger Level (V_{TH-}): When the output is low (close to GND):

$$V_{\text{TH-}} = \frac{R1}{R1 + \frac{R3\|R2}{R3+R2}} \times 0 = 0 \tag{5}$$

In this case, the lower trigger level is effectively 0 since the output is pulling directly to GND.

D. Relaxation Oscillator

The relaxation oscillator's oscillation frequency (f_{osc}) and duty cycle can be influenced by the time constant of the RC circuit and the comparator's trigger levels. Assuming $R1 = R2$ and an ideal comparator, the oscillation frequency is given by:

$$f_{\text{osc}} = \frac{1}{2RC\ln\left(\frac{2V_{CC}-V_{\text{TH-}}}{V_{\text{TH+}}-V_{\text{TH-}}}\right)} \tag{6}$$

where R and C are the resistor and capacitor values in the RC circuit, respectively, and $V_{\text{TH+}}$, $V_{\text{TH-}}$ are the comparator's upper and lower trigger levels.

VIII. Conclusion

A. Comparator with 1/2 Supply Trigger Level

In the experimentation with the first circuit, I hypothesized that upon inputting a triangular waveform, that the output would manifest as a square wave. My hypothesis was grounded in the premise that the comparator activates and deactivates when the input signal intersects half the supply voltage. The oscilloscope readings affirmed my expectations: not only was a square wave observed, but its positioning was also symmetrically centered within the triangular waves. This alignment is consistent with our understanding of the trigger mechanism and validates theoretical predictions.

B. Hysteretic Comparator

Proceeding to the hysteretic comparator, my theory postulated that this circuit, when subjected to a triangular waveform, would produce a square wave. However, the distinguishing factor of the hysteretic comparator is its trigger voltages. Specifically, the output turns high when the voltage reaches 1/3 of the supply and reverts to low at 2/3 of the supply voltage. Given this nuanced triggering behavior, I anticipated that the square wave output would be slightly offset from the midpoint of the triangular waveforms. The experimental data mirrored expectations, underscoring the consistency between theoretical insights and practical observations.

C. Relaxation Oscillator

The exploration of the relaxation oscillator showed its ability to produce a consistent square wave as a result of the rapid capacitor charging and discharging, combined with the feedback dynamics of the comparator circuit. The resulting waveform accuracy highlights the oscillator's potential in applications requiring precise timing and frequency control.