Comparator Hysteresis In A Nutshell

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The most fundamental basic building block of mixed-signal design is the comparator. It allows the transformation of analog signals to a digital form and is a straightforward device with two analog inputs and one digital output that, when coupled with the appropriative digital circuitry, can be used to measure period or frequency. Used with a DAC it can be used to construct ADCs. (It can, in itself, be thought of as a two state, or single bit, ADC.) It is ironic that this most basic system component can be the cause of so many problems. As an application engineer I constantly am dealing with customer's calls that go something like:

> *"I have my frequency meter working. It works great for large inputs, but for smaller amplitudes, it sucks!"*

Or, "*It works great until I slow down the frequency, and then its output value kind of doubles.*"

Or, "*Normally it runs fine but mistriggers whenever the fan motor turns on.*"

Or, *"My circuit doesn't work! What is wrong with your part?"*

I get all sorts of variants of this problem where the circuit performance degrades for lower signal frequency and amplitude, or some large system induced noise. If this is a problem you have faced before, this TechNote is for you.

A comparator is, fundamentally, an amplifier with a differential input and an extremely large open-loop gain. This high gain makes it extremely sensitive for comparing its inputs. For practical purposes (see Fig. 1) $\mathbf{V_p > V_n}$ causes the output to be driven to the positive supply rail. And, conversely, $\mathbf{V_p < V_n}$ causes the output to be driven to the negative rail.

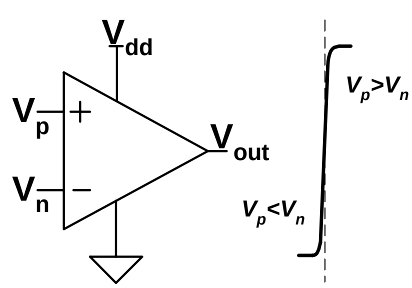

Fig. 1: Comparator Is A High-Gain Differential Amplifier

What about where $\mathbf{V_p}$ **equals** $\mathbf{V_n}$? Well "equal" is not a term analog guys have much use for. You won't find an analog guy ever say "exactly 50 V." (For that matter digital guys wouldn't either: they consider 50 V to be high-energy physics and refuse to touch the stuff.) A good working definition for "equal" is that brief period in the transition from "less than" to "greater than." (Or, for that matter, from "greater than" to "less than.") In this very narrow (typically 50 µV) transition span, the output is in its linear range. For the ideal comparator this transition width is zero.

Place a threshold reference voltage on the negative input and an analog signal to the other. The output will be logically high whenever the input exceeds this threshold. This is frequently done and can work without any problems.

Problems arise with noisy signals. Intuitively, for a slow moving input signal, noise can cause it to dance around the threshold, forcing the output to perform a digital cha-cha which offers nothing but grief for the system designer. This is a problem when the noise is relatively greater than the slope of the input signal and whenever the input amplitude is reduced or the noise level increased. The level of each is not important. What is important is the ratio of these to values. When the SNR gets below some value, mistriggering of the comparator results.

One solution is to increase the signal. However, the gain required for acceptable signal amplitude of the smallest possible input signal may cause the gain stage to saturate for larger signals: automatic gain control may be required. Another solution is to remove system and environmental noise, a task no harder than ridding the world of hunger.

A more practical solution is live with the noise. Suppose you had a comparator with two thresholds. One for transitions from low to high, and a lower threshold for transitions from high to low. The hysteresis is defined as the difference of these two thresholds.

$$V_{Hysterysis} = V_{UpperThreshold} - V_{LowerThreshold} \qquad \textbf{(1)}$$

If the hysteresis is greater than the noise seen at the input, the transition is guaranteed to be smooth.

A straightforward method to implement a comparator with hysteresis is to use two actual comparators and some digital logic[1].

The desired operation is:

- When the input is greater than the high threshold (**$V_{in} > V_H$**), the output is always high
- When the input is less than low threshold (**$V_{in} < V_L$**), the output is low
- When the output is low, the output will not go high until the input is greater than the high threshold
- When the output is high, it will not go low until the input is less the low threshold

A Boolean representation is given below:

$$Out = High + Out \cdot Low \qquad \textbf{(2)}$$

The implementation is shown in Fig. 2.

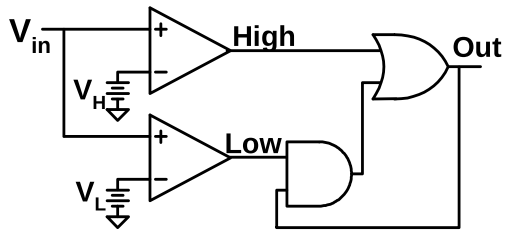

Fig. 2: Hysteresis Comparator Schematic

This is a very straightforward circuit but to implement it requires:

- Two references
- Two comparators
- Two logic gates

This is a lot of hardware to implement a single hysteresis compare function.

Another implementation is to use a single comparator but multiplex the desired reference. The comparator output controls which reference is used[2] (see Fig. 3).

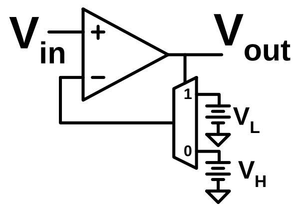

Fig. 3: Hysteresis Comparator Constructed With Multiplexer

While this implementation only uses one comparator, it still requires two references and an analog multiplexer.

Instead of using two references, a more efficient use of hardware would be to have one reference and some means to alter it. Just such a circuit is shown (Fig. 4).

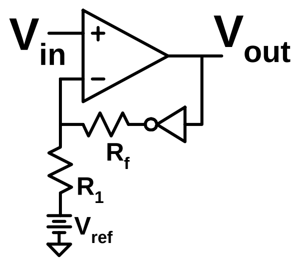

Fig. 4: Hysteresis Comparator Constructed With Single Reference

The resistor divider allows for a high threshold larger than the reference when the inverter output is high and a low threshold smaller than the reference when the inverter output is low. The ratio of these two resistors determines just how far these thresholds are pushed away from the reference:

$$
\begin{aligned}
V_{UpperThreshold} &= V_{ref} + \left(V_{OutHigh} - V_{ref}\right) \cdot \frac{R_1}{R_1 + R_f} \\
V_{LowerThreshold} &= V_{ref} + \left(V_{OutLow} - V_{ref}\right) \cdot \frac{R_1}{R_1 + R_f} \qquad \textbf{(3)} \\
V_{Hysterysis} &= \left(V_{OutHigh} - V_{OutLow}\right) \cdot \frac{R_1}{R_1 + R_f}
\end{aligned}
$$

The amount of hysteresis is determined by the comparator output swing and the resistive attenuation set. For a swing of 5 V, a 20% attenuator sets the hysteresis to 1 V.

With only a single comparator reference, two resistors, and an inverter this implementation is so far the most frugal with recourses. But pulling the inverter back through the comparator results in the inverting hysteresis comparator (Fig. 5).

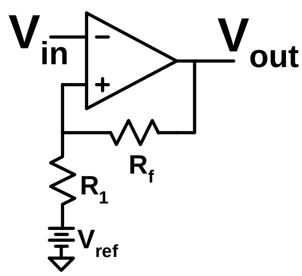

Fig. 5: Inverting Hysteresis Comparator Constructed With Single Reference

Dividing down the supply voltage with two resistors makes for an inexpensive reference. This results in a specific voltage and output impedance. It can be used to replace $\mathbf{R_1}$ and $\mathbf{V_{ref}}$ in the circuit above, resulting in the circuit of Fig. 6.

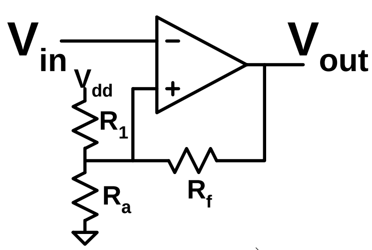

Fig. 6: Inverting Hysteresis Comparator Constructed With Three Resistors

Note that the topologies shown use some form of positive feedback. It would make sense to name this type of circuit a **Positive-Feedback Hysteresis Comparator.** The big problem with this is that your professors, back in your linear design classes, really stressed that negative feedback is good, and positive feedback is dangerously bad. They even had lab examples to prove it. To have an example that so blatantly contradicts them is something their delicate egos are just not all the comfortable with. The solution was to name this type of circuit a **Schmitt Trigger**. This allows for positive feedback to be used without having any professors losing face.

The following equations allow values to be selected given the high threshold, low threshold and supply voltage:

$$\frac{R_a}{R_1} = \frac{V_{LowerThreshold}}{V_{dd} - V_{HigherThreshold}} \qquad \frac{R_f}{R_1} = \frac{V_{LowerThreshold}}{V_{HigherThreshold} - V_{LowerThreshold}} \tag{4}$$

Suppose your requirements for a hysteresis comparator are to have a high threshold of 3.5 V and a low threshold of 1 V, given a 5-V supply. Entering these values in the above equations result in the following values:

$$\frac{R_a}{R_1} = \frac{1}{5-3.5} = 0.667 \qquad \frac{R_f}{R_1} = \frac{1}{3.5-1} = 0.400 \tag{5}$$

Setting **R_1 to 100 kΩ**, **R_a to 66.5 kΩ**, and **R_f to 40.2 kΩ** meets the desired requirements.

This circuit is implemented with a single analog block of a Cypress CY8C21534 configured to be a comparator. A 4.6-V 1-kHz sinusoid (centered around 2.5 V) stimulus is feed into the signal input. This signal along with the digital output are displayed in the oscilloscope screen shot in Fig. 7.

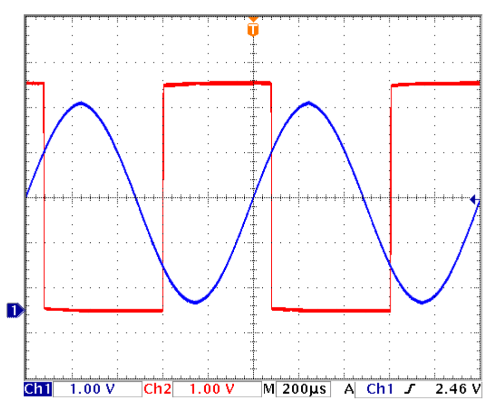

Fig. 7: Inverting Schmitt Trigger 3.5 V High Threshold, 1 V Low Threshold

Note that the output does not go low until the input exceeds 3.5 V and only returns high when the signal is less than 1 V. There are 2.5 V of hysteresis.

Comparator hysteresis allows for threshold detection in the presence of noise. The Schmitt trigger topology is straightforward to understand and easy be designed for specific threshold given the equation developed in this article.

References

[1] AN2210 *Comparator with Independently Programmable Hysteresis*, Dave Van Ess, Cypress Semiconductor, 2005
[2] AN2156 *A Switched Capacitor Comparator with Programmable Hysteresis*, Dave Van Ess, Cypress Semiconductor, 2004

About The Author

An Engineer by training, a poet by temperament, and an outlaw in Nebraska, Dave is capable of abstract thought, concrete analysis, and ruthless implementation. He earned a BSEE from the University of California at Berkeley and has more than 28 years experience in circuit, signal processing, digital, software, analog, and system design. Holder of six US Patents (plus three pending) for medical systems, signal processing, and digital block enhancements he is the author of numerous Application Notes, web casts, and technical articles. Dave joined Cypress Semiconductor at the dawn of the new millennium.