Physics 120 Lab 9 (2019): Positive Feedback, Bifurcations

9.1 Three Comparators and positive feedback

Comparators work best with positive feedback. But before we use these good circuits, let's look at two poorly performing comparator circuits: one using an op amp, the other using a special-purpose comparator chip. These circuits will help you to see what's good about the improved comparator that uses positive feedback.

Open-loop op amp as comparator

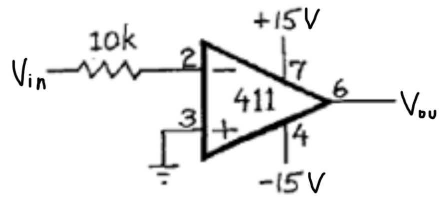

Figure 9.1: Op amp as simple comparator.

You will recognize this as the very first op amp circuit you wired (**Exercise 4.1**), where the point was to highlight the high gain of the device. In that exercise the excessive gain was factored out of the circuit equations and the input/output was linearized. Here we view the circuit as a comparator and the very high gain and the "pinned" output are desired.

Drive the circuit (LF411 or AD711) with a sine wave with a 100 mV (or less) amplitude at around 100 Hz and notice that the ouput is close to a "square wave"; document with a **SCREENSHOT** (**1 pt**). Now drive the circuit at 100 kHz, and document with a **SCREENSHOT** that the "square wave" output is not as square as it was for 100 Hz (**1 pt**). Why not (**1 pt**)?

Special-purpose comparator IC

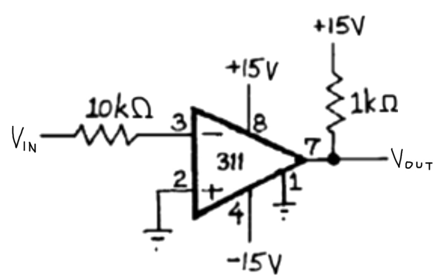

Figure 9.2: 311 comparator and no feedback.

Now substitute a LM311 comparator for the op-amp; the pin-outs are *not* the same. You will notice that the output stage looks funny: it is not like an op amp's, which is always a push-pull; instead, two pins are brought out, and these are connected to the *collector* (pin 7) and *emitter* (pin 1) of the output transistor, respectively. These pins let the user determine both the maximum and minimum output swing, e.g., one can use +3 V and ground to make the output compatible with standard digital logic).

Here, you will keep the top of the swing at + 15 V and set the *bottom* of the swing to ground. Does the LM311 perform better than the LF411 (**1 pt**)? How so (**1 pt**)? Document the improvement in gain(s) with a **SCREENSHOT** (**1 pt**).

A side-effect of the LM311's fast response is its readiness to oscillate when given a small and/or voltage difference between its inputs. Tease your LM311 into oscillating near the transition using a sine wave with a *gentle slope*. You may need to use the "expansion settings" of the oscilloscope. Document your output with a **SCREENSHOT** that shows rapid transitions near the threshold (**2 pts**).

Special-Purpose Comparator IC configured with positive feedback as a Schmitt Trigger

The *positive feedback* used in the circuit of Figure 9.3 provides hysteresis that will eliminate the harmful oscillations by shifting the threshold immediately after a transition. Predict the thresholds of the circuit above (see class handout as a guide but *derive* the expression for this simplified case) (**2 pts**); they try it out and document your a functioning circuit with a **SCREENSHOT** (**1 pt**).

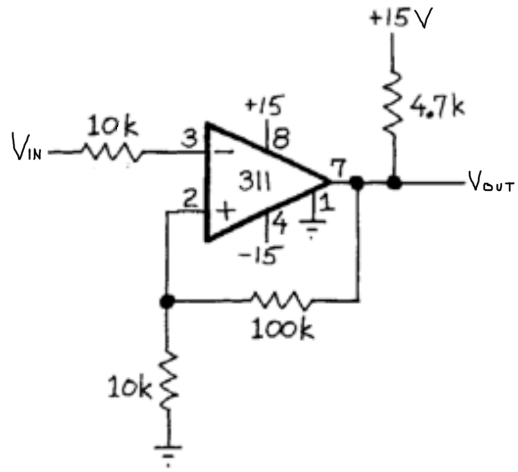

Figure 9.3: Schmitt trigger: comparator with positive feedback

Notice that triggering stops for sine waves smaller than some critical amplitude. Explain this (**1 pt**). Measure and report the hysteresis (**1 pt**). Observe the rapid transitions at the output, independent of the input waveform or frequency. Look at both the "-" and "+" comparator terminals and document with a **SCREENSHOT** of the V_- and V_+ inputs and the output (**2 pts**).

Reconnect the so-called "Ground" pin of the 311 to - 15 V; this pin is not necessarily ground, rather it is the emitter of the output transistor. This is why the chip's designers brought out this pin, as well as why they provided an *open-collector* output.

9.2 Relaxation oscillator

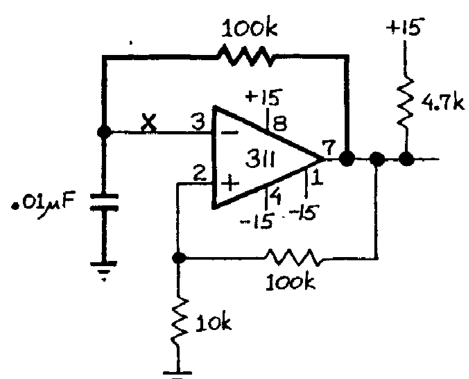

Figure 9.4: RC relaxation oscillator

A comparator is used with positive feedback to construct a free-running oscillator. Build the circuit of Figure 9.4 and show, with a **SCREENSHOT**, that V_{out} oscillates (**2 pts**). What are the expected and measured frequencies (see, *e.g.*, class notes) (**1 pt**)? Record from both the output and point "X" and explain, documenting with a **SCREENSHOT** (**1 pt**), what you see. Repeat, including **SCREENSHOT**, with the 10 kΩ resistor replaced with 1 MΩ (**1 pt**).

9-3 7555 IC oscillator (square wave)

The 555 and its derivatives have made the design of moderate-frequency oscillators easy through the use of a monolith device. The 7555 runs up to 500 kHz and its very high input impedances and rail-to-rail output swings can simplify designs.

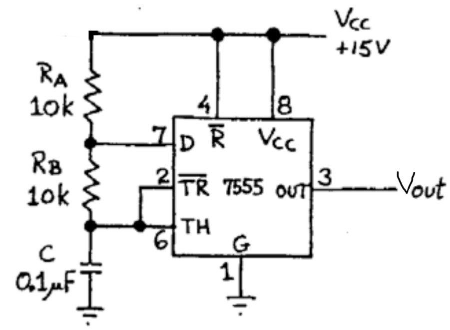

Figure 9.5: 7555 relaxation oscillator.

Connect a 7555 in the classic relaxation oscillator configuration, as shown above. Look at the output and document with a **SCREENSHOT** (**1 pt**). The frequency is given by:

$$f_{oscillation} = \frac{1.4}{(R_A + 2R_B)C}$$

Look at the waveform on the capacitor (**C**). What voltage levels does the waveform vary between (**1 pt**)? Document with a SCREENSHOT. Do these levels make sense (**1 pt**)?

Replace $\mathbf{R_B}$ with a short circuit. What do you expect to see at the capacitor (**1 pt**)? At the output (**1 pt**)? Document these conclusions with **SCREENSHOT**s.

9-4 Subharmonic generation

We previously investigated (**Harmonic analysis and diode circuits Laboratory**) how a diode can be used as a rectifier. Rectification of a sinusoid, with frequency f, introduces higher harmonics, i.e., $2f$, $3f$, etc. We now make use of another property of the diode, i.e., the decrease in capacitance across the p-n interface with an increase in reverse bias potential, to generate subharmonics, i.e., $f/2$, $f/3$, etc.

Our experimental system is a series L-C-R circuit driven by a sinusoidal oscillator. It is described by

$$L\, d^2Q/dt^2 + R\, dQ/dt + V_D = V_0\, sin(2\, p\, f\, t),$$

where V_D is the voltage across the diode with $V_D = (k_BT/e)\log[d(Q/I_0)/dt + 1]$ where I_0 is the reverse bias current Under reverse bias voltage the p-n junction functions as a capacitor to pass an alternating current, with $C(V) \sim C_J(0)/\sqrt{(1-V_D/V_I)}$ where $C_J(0)$ is the junctional bias at zero voltage and V_I is the junction potential. Under forward bias the diode will conduct.

For our realization, we use a 1N4004 diode, with $C(0) \sim 20$ pF and $V_I = 0.6$ V. Each coil has a nominal inductance of 10 mH and a nominal resistance of 150 Ω, yielding L = 20 mH and R = 300 Ω. At low values of applied voltage V_0 the system behaves like a resonant circuit, i.e., for $V_0 << k_BT/e = 25$ mV. As V_0 is increased, C(V) decreases and the resonant frequency shifts upward. It is not our intention to solve the intractable non-linear differential equations for this system. Rather we will make extensive measurements to study bifurcations to period doubling, tripling, etc.

Build the circuit (**Fig. 9.6**) and record V_{in} and V_{out}. Determine the resonance frequency, denoted f_0, for the circuit using $V_0 = 10$ mV (**1 pt**); compare with $1/\sqrt{LC(0)}$ (**1 pt**). What is the expected phase-shift between V_{in} and V_{out} at resonance (**1 pt**)?

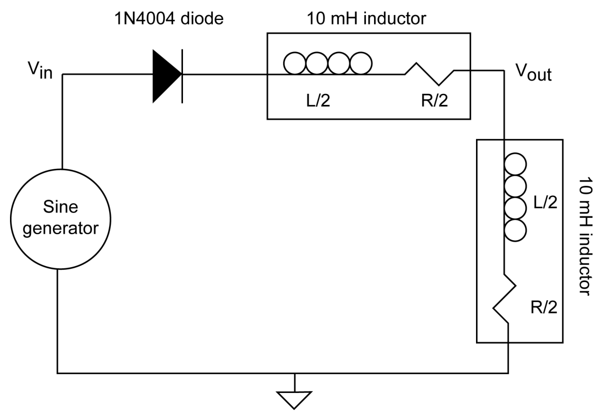

Figure 9.6. A circuit to generate subharmonics.

Use the "Acquire" function to shift the display of the oscilloscope between "X-Y", i.e., V_{out} versus V_{in}, and "X-T", i.e., the usual V_{in} versus time and V_{out} versus time. Set the frequency to about 1.15 f_0 and slowly ramp up the voltage. *Note 1: transitions occur abruptly with changes in V_0. Note 2: You will need to adjust the gains on the channels as V_{in} changes, there is a lot of "back and forth" with controls on the oscilloscope with this exercise.* Document the transitions to frequency doubling, tripling, quadrupling, and quintupling, both as "X-Y" and "X-T" **SCREENSHOTs** (**8 pts**); see **Figure 9.7** for examples. Intermediate voltages will lead to complex behavior - have fun and go wild!

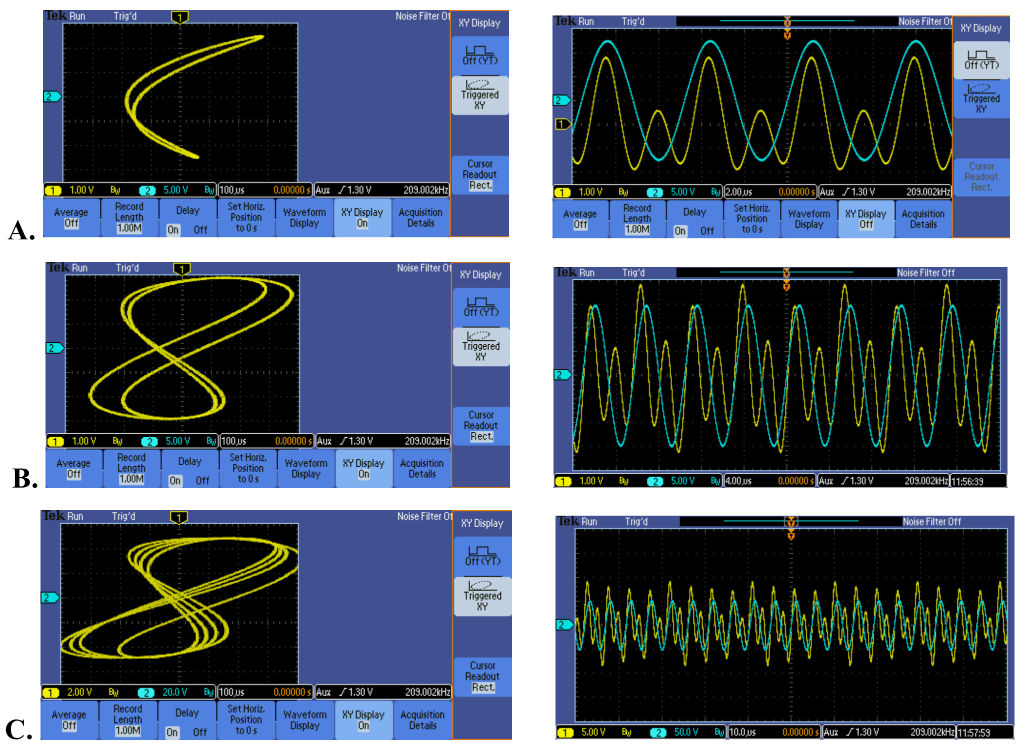

Figure 9.7. Examples of data for V_{in} and V_{out}, plotted as "X-Y" and "X-T" (blue trace is V_{in} and yellow trace is V_{out}) when the fundamental of V_{out} is **(A)** f_0, **(B)** $f_0/2$, and **(C)** $f_0/4$. Parameters were f_0 = 179 kHz, f = 208 kHz, V_0 = 1.25 V, 2.78 V, 4.66 V, and 7.41 V for the transitions to the second through fifth subharmonics.

35 points total