GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL of ELECTRICAL and COMPUTER ENGINEERING

ECE 4893A: Analog Circuits for Music Synthesis   Spring 2018
Problem Set #2

Assigned: 14-Feb-18
Due Date: 21-Feb-18

Your homework is due at the *start* of class on **Wednesday, February 21**.

Words in a typewriter-style font are hyperlinks; clicking on them in your PDF reader should open them up in your default web browser.

Background music: The original Buchla Music Easel, which consists of a Buchla 208 Programmable Sound Source and a Buchla 218 Model Keyboard together in a single case, is one of the rarest and most coveted of the Buchla designs. (It has recently been re-released.) To put yourself in the right frame of mind for this homework, listen to `this video` featuring former Nine Inch Nails synthesist Alessandro Cortini performing on his Music Easel.

Ground rules: You are free to discuss approaches to the problems with your fellow students, and talk over issues when looking at schematics, but your solutions should be your own. In particular, you should *never* be looking at another student's solutions at the moment you are putting pen to paper on your own solution. That's called "copying," and it is bad. Unpleasantness, including referral to the Dean of Students for investigation, may result from such behavior. **In particular, the use of "backfile" of solutions from homeworks and quizzes assigned in previous offerings of this course is expressly forbidden.**

PROBLEM 2.1:

In class, we looked a sawtooth VCO core design from Hal Chamberlin's "Musical Applications of Microprocessors." In this problem, we'll look at Ray Wilson's 1V/Octave Voltage Controlled Oscillator, which is another sawtooth core design:

`https://web.archive.org/web/20111018143957/http://www.musicfromouterspace.com/analogsynth/VCO200604REV01/VCO200604REV01.html`

This is a very complicated circuit, so we'll rely on Ray's thorough description, which you should read. Check out the LM394 in the Page 1 schematic:

`https://web.archive.org/web/20080725011720/http://musicfromouterspace.com/analogsynth/VCO200604REV01/VCO20060319_WMODS_pg1_schem.pdf`

This forms the core of the exponential converter (note Ray later discovered that the SSM2210 works better). Call the current flowing into pin 1 of the LM394 I_{freq}. (Hint: you may use Ray's "1.1 volt" figure.)

(a) Given Ray's description of the circuit operation, find the frequency of the oscillator in Hertz in terms of I_{freq}. (To make things easy, assume the reset time is zero.)

(b) Given your result in part (a), what value of I_{freq} would generate a 440 Hz tone?

(c) Now let's get some practice in reasoning with tempco resistors. In the example exponential converter shown in class, the tempco resistor was used in a resistive divider just before one of the bases of the transistor pair. Here, Ray decided instead to use the tempco resistor in the feedback loop of an op amp. Suppose that R8, R10, R18, R23, R27 aren't there, and we'll focus just on the CV1 input through R15. What is the output of U1-A (pin 1) as a function of voltage CV1 if the tempco is at a temperature of 25 degrees Celcius (the base resistance is 2K for 25 degrees Celsius)?

(d) Now suppose you're using Ray's VCO circuit to make sound for an art installation at the Burning Man Project, which can get up to and above 100 degrees Fahrenheit during the day. Redo problem (c), except use a temperature of 40 degrees celcius instead of 25 degrees celcius.

PROBLEM 2.2:

In class, we looked at exponential converters, particularly a current "sink" that used a matched NPN pair. In this problem, we will look at a current "source" that uses a matched PNP pair; the same sort of thinking we used in class also applies to this variation. J.G.N. Bergfors, the creator of the `Bergfotron`, conducted a `VCA shootout` comparing various VCA designs. Let's take a look at CA3080 VCA 1:

`http://hem.bredband.net/bersyn/VCA/ca3080%20vca%201.htm`

The exponential converter is at the top of the schematic, and the main VCA is at the bottom part of the schematic. The power supply voltages are not marked on the schematic or on the webpage, but based on J.G.N.'s power supply design, let's assume the VCA uses a +/- 15 V supply.

The exponential converter takes a control voltage CV (found in the upper left of the schematic) and generates a control current for the OTA of the form $I_{con} = I_{ref} \exp(const \times CV)$.

(a) What is I_{ref}?

(b) Assuming that the CV offset trim pot is set all the way to the "right" (i.e. at ground), what change in CV will cause the control current to double? (Assume the PNP BJTs draw insignificant current through their bases).

(c) Assuming the OTA is operating in the linear region, give an expression relating the audio output voltage to the audio input voltage in terms of the current at the control input pin of the OTA. (You may ignore the offset trimming circuitry of the OTA. Assume the positive input of the 3080 is grounded.)

(d) What is the input impedance of this VCA?

(e) What is the output impedance of this VCA? (It might be "0" - remember we're assuming ideal op amps.)

PROBLEM 2.3:

In class, we looked at the triangle VCO core of the Buchla 259. That oscillator is designed to operate at audio rates. In this problem, we will look at a voltage-controlled "low frequency oscillator" (LFO), which is a particular kind of VCO. Although some LFOs can run at it can run at lower audio frequencies, they're typically not designed with the rigorous requirements needed to play "in tune." Instead, they're usually intended to provide control voltages to control other parameters (such as the pitch of an audio VCO to create a police siren.)

Let's look at one of Ray Wilson's old VC-LFO designs:

`http://web.archive.org/web/20101228090349/http://www.musicfromouterspace.com/analogsynth/VCLFO200607/VCLFO200607.php`

The main triangle core is on the left half, midway between the top and the bottom. C11 and U2-A form the integrator. (I'm not sure why the R22 is there, so let's ignore it in our analysis). Let's call the output of U2-A (pin 1) V_{tri} (I'm using the underscore to indicate a subscript).

Notice that U4-A is not being used in a negative feedback configuration, so the "golden op amp rules" do not apply. U4-A is being used as a comparator, so the output of U4-A (pin 1) will try to snap to the positive supply (+12 V) if the voltage at pin 3 is greater than pin 2, and try to snap to the negative supply (-12 V) otherwise. Now, in reality, the TL082 is not a so-called "rail-to-rail" op amp. Take a look at simplified schematic of the National TL082 datasheet on my Datasheet Archive – you'll see there's a NPN BJT between the output and the positive supply and a PNP BJT between the output and the negative supply. Hence, we'd expect that the output could swing to at most within a "diode drop" of the supply lines (in this case, assuming a 0.7 V diode drop, -11.3 V to 11.3 V). Based on the "output voltage swing" line on the datasheet, I'm guessing it's closer to something like to within 2 volts of the supply. So, let's suppose that the comparator outputs +10 V or -10 V.

Let's suppose that the Tri Skew trim pot is set to the middle. Assume that the diodes are either "off" (in which case no current flows through them) or "on" (in which case we'll assume a "diode drop" of 0.7 V).

Assume the OTA has infinite input impedance. Ignore the C10 cap in the feedback loop of the comparator op amp (U4-A).

(a) When the output of the comparator is +10 V, what is the **voltage at the positive input terminal of U3-A?**

(b) When the output of the comparator is +10 V, using the nonlinear "tanh" model for OTA behavior, what is the output current of the OTA as a function of the current control input (pin 1) of the OTA? (Note that unlike the Buchla 259 VCO circuit we looked at in class, the OTA here does not seem to be fully saturated.)

(c) When the output of the comparator is +10 V, what voltage at the output of the integrating op amp (pin 1 of U2-A) would cause 0 V to appear at the positive terminal of the comparator op amp (pin 3 of U4-A)? (Note that this will tell you the maximum level of the triangle wave).

(d) What is the frequency of the triangle wave as a function of the current control input (pin 1) of the OTA?

(e) Take a look at the TRI output in the middle of the page (pin 2 of R15). What is the output impedance of the TRI output?

PROBLEM 2.4:

In this problem, we will explore the `Advanced VCO` of the `Bergfotron`. In particular, we will investigate a very small part of the schematic of its waveshapers:

`http://hem.bredband.net/bersyn/VCO/AVCO%20waveshapers_s.pdf`

There's a lot of freaky stuff on that schematic. We will concern ourselves with the op amp labeled IC2 in the middle of the page (the TL072 is a dual op amp; we will not worry out the op amp in the upper right corner). This IC2, along with some additional circuity, claims to produce a sawtooth wave, labeled "SAW OUT," from the triangle wave produced by the Advanced VCO's core.

Let's denote the output signal labeled "TRIANGLE OUT," which is produced by half of IC9 (not to be confused with the IC9 in the upper left corner of the page), as V_{tri} (where I am using the underscores to indicate subscripts). Let's denote "SAW OUT" as V_{saw}.

The square wave produced by the Advanced VCO's core controls the 4066 CMOS switch; for this case, focus on the switch corresponding to pins 3, 4, and 5 (pin 5 is the control). The 11K resistor and 22p capacitor in the feedback loop of IC2 seem to form a lowpass filter; however, computing the cutoff of this filter yields a cutoff of 658 kHz. This is far above the range of human hearing, so I presume the 22p capacitor is there for stability and general gremlin-eating. So, let's ignore (i.e. open) that capacitor.

The 20K and 68K resistors attached to pin 2 of IC2, and the 4.7M, 13K, and 24K resistors attached to to pin 3 of IC2, will all play a role in this problem. The circle with a + in it connected to the 4.7M resistor is the +15 volt power supply; the circle with the - in it connected to the 68K resistor is the -15 volt power supply.

(a) Find V_{saw} as a function of V_{tri} when the 4066 connected to the 13K resistor is switched OFF. (Assume its OFF resistance is infinite.)

(b) Find V_{saw} as a function of V_{tri} when the 4066 connected to the 13K resistor is switched ON. (Assume its ON resistance is zero).

PROBLEM 2.5:
In class, we looked at a nonlinearity implemented using diodeless deadband circuits that appears in the Buchla 259 Programmable Complex Waveform Generator and the Buchla Music Easel described above. In this problem, we will explore the details of the circuit implemented in the Music Easel.

In this problem, you can print out the schematic from Magnus's Buchla page:

`https://rubidium.dyndns.org/~magnus/synths/companies/buchla`

Ssearch for the "B2080-9A' Complex Oscillator 3/3" link on that webpage. You'll see five of those "Buchla diodeless deadband" circuits.

Let's analyze the topmost deadband circuit, which consists of an op amp and R25, R27, and R26. **Calculate the positive edge of the deadband** (i.e., what is the largest input voltage for which the output stays zero?), and **calculate the slope of the output/input curve past that point.** As in lecture, let's define the "output" as the voltage at the negative input of the op amp forming the deadband circuit, and the "input" as the voltage at the output at the op amp just above resistor R20 on the schematic. You may adapt the formulas we derived in class; you don't have to derive them from scratch.

Important warnings:

- Remember in Buchlaese, that when two lines cross without a dot, they don't electrically connect; when two lines meet at a T-intersection without a dot, they do electrically connect. "Q" usually represents "quiet ground" (for analog signals) and "N" usually represents "noisy ground" (ground for digital logic and return paths for current-thirsty devices like light bulbs).
- The Buchla 259 used CA3160 op amps, which enjoy "rail to rail" output swings due to their CMOS output stage, run with "voltage starved" supplies of 6 V and -6 V. The Easel appears to use RC4136's instead, and although the power supplies are not explicitly marked, I'm told they run off Buchla's usual +15 V and -15 V. With the exception of one JFET, the rest of the circuit for the RC4136 shown on the datasheet seems to be all bipolar, so I doubt it can do the "rail to rail" business that the CA3160 can. Elsewhere on the sheet, I see that the "maximum peak output voltage swing" is listed as being "minimum +/- 12 V" and "typical +/- 14 V" for a 10K load. The resistors I see on the sheet are all higher than 10K, suspect they're running more towards what's listed as "typical." Looking at the schematic on the datasheet, I see that the output is sandwiched between two BJT's between the supply rails, so there's at least a diode drop there from the possible output to the rails. So... let's use -14 V and 14 V as the output voltage limits (as opposed to the -6 V and -6 V volts we saw in the case of the 259).
- Notice a few of the "resistors" are actually a couple resistors in parallel. (Do you get the impression that Buchla might have started with a basic design, and then tweaked it by throwing in a few more resistors here and there?) It's not relevant for the exact problem I asked; I just thought this was an interesting observation. Interestingly, the 259 had both "timbre" (amplitude of sinewave going in) and "symmetry" (DC offset on sinewave going in) controls; the Easel appears to just have a timbre control.