Lab 7

November 3, 2018

Integrator Circuits

In this lab we will begin to explore the time domain using the follower integrator circuit. It is simply a transconductance amplifier with capacitor on the output, to implement a first order lowpass filter.

The objectives of this lab are to:

- Learn how to use the Tektronix TDS 300 Series Digital Oscilloscopes and the HP 33120A Function Generator. (Already introduced in current-mode and WTA lab.)
- Understand the behavior of the first-order lowpass follower-integrator circuit in the time and frequency domain in small and large signal operation. *Lowpass* means that the circuit passes low frequencies and blocks high frequencies. *First-order* means that the transfer function amplitude decreases like 1/frequency. *Follower-integrator* means that the filter follows at low frequencies, and integrates (averages) at higher frequencies.
- Understand how a follower-integrator can be used as a differentiator, or high-pass filter by changing the connections.
- Understand the *large signal behavior* and other limitations of using a transconductance amplifier to model a linear resistor.

7.0.1 Reading

See Chapters 8 and 9 of the Carver Mead book ('Analog VLSI and Neural Systems'), paying particular attention to the time and frequency domain treatments of the RC circuit, pages 129-130 and 137-140 in Chapter 8, and the follower-integrator circuit, pages 147-149 and 158-162 in Chapter 9. Slides are also available introducing linear systems analysis.

7.0.2 Prelab

1. How are capacitors constructed in CMOS chip technology? There are several different possible implementations. How are they constructed in neurons? What is the capacitance per square micron of a SiO_2 capacitor with oxide thickness of 10nm? What

is the capacitance per square micron area of a lipid-bilayer capacitance with thickness of 5nm? (You will need to look up the dielectric constants for SiO_2 and lipid bilayers; remember to provide your sources in your writeup. One standard source for lipid bilayers is Ohki, Shinpei. "Dielectric constant and refractive index of lipid bilayers." Journal of Theoretical Biology 19.1 (1968): 97-115[1].)

2. Derive the transfer function $H(s) = V_{out}/V_{in}$ for the follower-integrator, using the s-plane notation, expressed in terms of complex frequency s and the time constant τ.

3. Compute the transfer function $H(s) = V_{out}/V_{in}$ for the follower-differentiator, using the s-plane notation, expressed in terms of complex frequency s and the time constant τ. The follower differentiator is the same circuit as the follower integrator, except that the input is to the capacitor plate that was tied to ground, while the amplifier positive input is tied to a reference voltage, which now sets the DC output voltage.

4. Compute the magnitude $|H(s)|$ for the follower integrator for input angular frequency ω. At what frequency f in Hz does the power drop to half its low frequency value?

5. Compare the simple RC integrator, constructed from a resistor and a capacitor, and the follower-integrator to show how the transfer function falls short in describing the follower integrator. In particular, how does the follower integrator respond to large signal inputs? This question is related to the next one, which is

6. What does "small-signal" mean? In other words, what voltage range will this regime correspond to? For the follower-integrator circuit is it the amplitude of the input or the output or the difference between the two that matters? Why?

7.1 Experiments

In the following experiments you will be using the oscilloscope. Keep in mind that the digital oscilloscopes allow you to subtract a large digital DC offset from a signal. You may prefer to use this DC offset subtraction to observe signals, especially at low frequency. You may also want to make sure that your scope probe is properly compensated, by using the scope's built-in compensation source. Watch out that your scope is not set to *AC coupling* when you don't want this; the AC coupling corner frequency is typically around 1Hz.

7.1.1 get_scope

You can use the matlab mex function *get_scope* to grab scope data. E.g.
[time, voltage]=get_scope('tds1',1); plot(time,voltage); xlabel 'time (s)'; ylabel 'volts'

These two commands grab scope channel 1 and then plots it. The first argument *tds1* is the name of the oscilloscope in the file */etc/gpib.conf*. The mapping from oscilloscope name to

[1] https://www.sciencedirect.com/science/article/pii/0022519368900088

GPIB address (by our convention address 11) is in this file[2] The second argument *1* is the scope channel.

To get help, type `>> help get_scope`
which will print the *get_scope.m* file contents which just documents the mex file. Or just run *get_scope* to see a usage message.

Experiment 1: The RC integrator

This experiment examines the time-domain behavior of a linear RC integrator built from discrete off-chip components. Build your integrator using a resistor and capacitor supplied by your TA. You should have an *RC* time constant of about 0.1ms=1e-4s. Use a low amplitude square wave as input to the RC integrator and measure the output with the oscilloscope, as shown in Fig. 7.1. Use the SYNC output of the HP function generator as the external trigger for the scope (EXT TRIG input). Display the input and output voltage waveforms on the scope and adjust the HP33120A's frequency so that the integrator's time constant τ is about 20% of the high or low half of the cycle. In other words, adjust the period so that the rise time of the output waveform can be seen and the output rises to about the same maximum amplitude as the input waveform. Capture both waveforms and hand in a single plot showing both signals. Annotate your plots showing the time constant.

Determine the time constant of the circuit $\tau = RC$ by fitting the theoretical solutions to your data and compare with the value calculated from the nominal values of the resistor and capacitor. One way to do this fit is to plot the difference between the signal and the final DC value on a log scale, and then finding the slope of this line. Since the signal approaches its final value exponentially, according to $V(t) = V(0)e^(-t/\tau)$, you can find τ from the slope of the log of $V(t)$. The slope in $1/s$ is exactly $1/\tau$.

plot182

You can make a function for the full response and then fit using a matlab data fitting toolbox, restricting your data range to the rising or falling edge. But if you plot using the locally-developed matlab function *plot182*, then you can read the slope easily with the mouse. The function *plot182* is in the folder ~/Documents/functions/MPlot182/. After you plot your data, e.g. with *plot182(t,v)*, then type *control-m* in the plot window to enter measurement mode. Now drag your mouse to measure a slope, which is shown in the lower right corner of the plot. Escape this mode by typing space. Change to a log scale with *control-l*. Other items are in the new menus that *plot182* adds to the right of the normal ones in the plot window. You can type *plot182* by itself after you do a normal plot to add the *plot182* functionality to any normal plot.

[2]For the TAs: The source code of get_scope is in `https://svn.ini.uzh.ch/repos/hw/class/sw`. For troubleshooting the getScope function, see the global class wiki troubleshooting page at `http://avlsi.ini.uzh.ch/classwiki/doku.php?id=troubleshooting`.

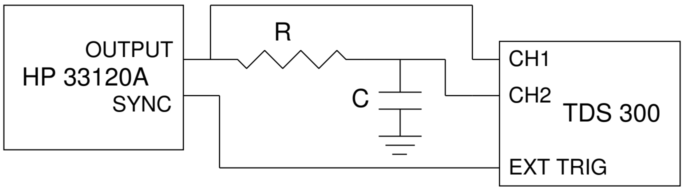

Figure 7.1: RC-integrator test circuit.

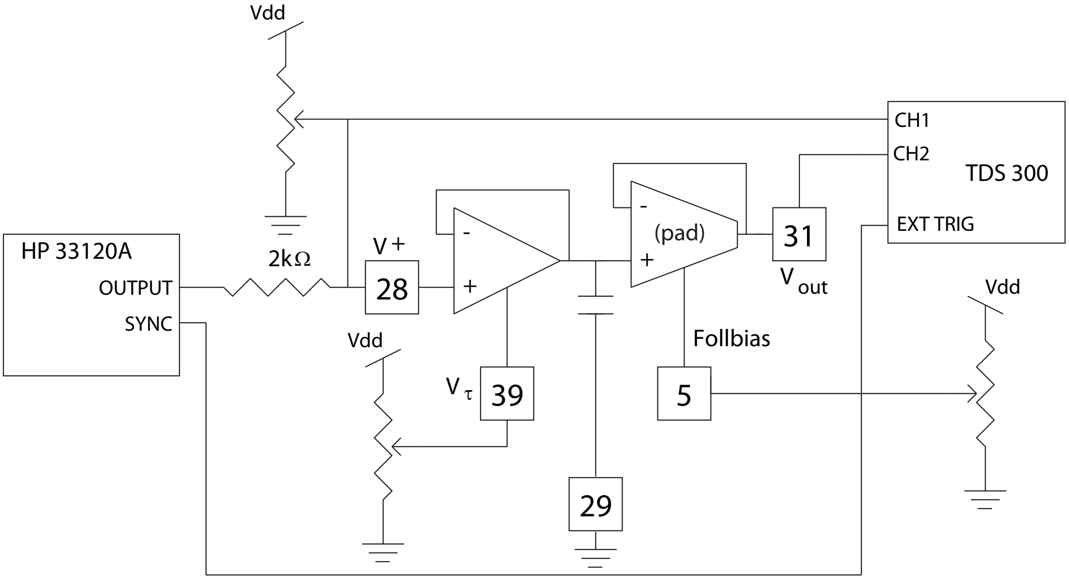

Figure 7.2: Follower-integrator test circuit on test chip Classchip 2005rev1.

Experiment 2: Time-domain response of follower-integrator

This experiment examines the time-domain response of a follower-integrator circuit (Fig. 7.2). You will be using Classchip 2005rev1 this week. The circuit you will be testing consists of a wide-range transconductance amplifier with a capacitor at its output. As always, there are only a limited number of chips so please be careful! The V_{dd} connection is on pins 25 and 35, the ground connection on pin 15. The PadBias connection is on pin 5. Also connect pin 40 to ground to completely shut off the neuron circuit.

Supply a square wave to the input using the HP signal generator. The HP signal generator has limitations on the amplitude of a signal with respect to the DC offset. In order to get small signal amplitudes we will have to supply our own DC offset. We will do so by applying a DC offset with a potentiometer (about 2V) and then superimposing the output of the function generator on top of it. This arrangement is shown in Fig. 7.2. Be sure to measure the input signal at the chip – not at the function generator – because the 2kΩ resistor attenuates the signal by a factor of 2 or so. The circuit's output is buffered by a follower pad (a large OTA configured to unity gain) so you must set the Follbias knob (pin 5) to about 1V. If you set Follbias too large, your output will be attenuated because the follower pad circuit will run too far in superthreshold, reducing its voltage gain.

Place a subthreshold bias on the V_τ knob (pin 39); about 0.5V will do nicely. Apply a small amplitude square wave – about 100mV peak to peak *when measured at the input*.

NOTE: The function generator assumes by default that it drives a 50 Ohm load, you'll have to program the HP for half the voltage difference that you want at it's output. E.g. for 100mV peak to peak you program it for 50mV, because the function generator has an output impedance of 50 ohms and outputs a voltage double what you program so that it would result in the displayed voltage if it were driving a 50 Ohm load. Since the load it actually drives is much higher (kOhms), then the result is a voltage that is about double what you program. But remember that here you also have a resistive divider which will lower the signal amplitude.

Adjust its frequency so that τ is about 20 per cent of a half-cycle, i.e., the signal can settle then for 5τ on edge edge. Display both input and output waveforms on the oscilloscope (using DC coupling with offset subtraction or AC coupling). The signals will be very noisy, about 10mV of noise is normal, so you have to average several traces to get a good measurement (You can do this using the scopes average function in the 'acquire' menu) . Capture the averaged trace into MATLAB, plot the curves, and determine the time constant τ of the integrator.

Is there any difference between the rise and fall times? Looking at the circuit, what could cause this mismatch of rise and fall behavior?

Experiment 3: Frequency-domain response of the follower-integrator

In this experiment you will examine the frequency-domain response of the follower-integrator. You don't have to modify your setup at all – just use a sine wave instead of a square wave. Measure the input and output amplitudes at ten or more different frequencies around the cut-off frequency. (You can quickly determine that by eye or start from the calculated value $f_{3dB} = 1/(2\pi\tau)$). E.g. if $\tau = 1$ms, then $f_{3dB} = 160$Hz.) Start a decade below the cut-off frequency and take data over at least two decades, doubling the frequency between successive points.

Plot your data on a log–log graph and determine the frequency at which the gain decreases by $1/\sqrt{2}$ and the corresponding value of τ. How does your value for τ compare with that from Experiment 2?

Experiment 4: Large signal behavior of follower-integrator

This experiment examines the *large-signal* behavior of the follower integrator and anomalous behavior at low input voltages. You don't need to change any connections. Apply a large amplitude square wave (> 400mV peak-to-peak) to the integrator. Observe that the behavior is no longer exponential. Explain your results in terms of the limiting behavior of the amplifier. Plot the response, showing the linear and exponential regions. Notice that the slew rates for up and down-going signals may be different. Explain why and determine their ratio. *Hint: It is either due to the Early effect or to device mismatch!*

Leaving the amplitude of the input signal at the large-signal level, turn up the τ knob (pin 39) until the output faithfully follows the input. Now decrease the DC level of the input. Capture traces of any strange behavior you observe and explain it. Consider the useful operating range of the transconductance amplifier. You should use DC coupling here to plot your results showing the DC levels of input and output. *Hint: consider what happens when the bias tail current transistor goes out of saturation.*

EXTRA CREDIT: How slow can you integrate? (We invite anyone who can can convincingly answer this post-lab exercise to write a conference paper about the result with us.)

Try decreasing the bias current of the follower integrator. How slow can you make the circuit? What happens to the steady-state DC offset between input and output when you make the follower integrator very slow? Is the offset a function of the input DC voltage level? If the input is a square wave, is the average of the output equal to the average of the input? Can you explain why this is happening?

How is the offset affected by temperature? And by shining light onto the chip? It is known that reverse-biased junction leakage doubles every 6-8 deg C around room temperature. You can use the heat gun from the workshop to gently heat up the chip. Watch out, if you set the gun to high power, it can melt solder and burn plastic! If you shine light onto the chip, all junctions will leak to their local substrate very quickly.

7.2 Postlab

1. The continuous-time RC or follower integrator acts as an *integrator* over only a certain frequency range. What is this frequency range and what happens for frequencies outside this range?

2. You may have noticed a difference in the up and down-going slew rates in the follower integrator. Do you expect this difference to show up in the rise and fall time constants for linear operation of the circuit?

3. The asymmetry in the slew rate means that for large signals, the average voltage of the follower-integrator output (it's DC value) will not be equal to the average level of the input voltage. Explain why.

4. How would running the follower-integrator above threshold change the small and large signal operation of the circuit?

5. As you computed in the pre-lab for the follower-differentiator, if you turn the RC integrator around, the RC integrator can be used as a CR differentiator. Diagram how

and compute the frequency range over which the CR differentiator actually differentiates. Also diagram the equivalent follower-differentiator. What happens outside this range of frequencies?

6. Sketch the simplest bandpass filter you can build using two transconductance amplifiers and two capacitors, by combining a follower-integrator with a follower-differentiator in series. Sketch the magnitude transfer function and indicate the corner (high-pass) and cutoff (low-pass) frequencies.

7.3 What we expect you to remember

How to use an oscilloscope and a function generator. How to compute the time-constant of a first-order low-pass filter and how to estimate it from the measurements. How to change the time-constant of a follower-integrator circuit. In what way does the follower integrator behave nonlinearly for large signal input? What is a follower-differentiator and how is it related to the follower-integrator? In what way is a low pass filter like an integrator and a high pass filter like a differentiator? What are the responses of the follower integrators and differentiators to large signal stimuli?

7.4 Next Week

Introduction to phototransduction with silicon.