Integrator Circuits

In this lab we will begin to explore the time domain.

The objectives of this lab are to:

- Learn how to use the Tektronix TDS 300 Series Digital Oscilloscopes and the HP 33120A Function Generator.
- Understand the behavior of the follower-integrator circuit in the time and frequency domain in small and large signal operation.

7.0.1 Reading

Information about this subject can be found in the class-script and in 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.

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 SiO2 capacitor with oxide thickness of 10nm? What is the capacitance per square micron area of a lipid-bilayer capacitance with thickness of 50nm? (You will need to look up the dielectric constants for SiO2 and lipid bilayers.)

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

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

4. 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.
5. 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 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.

#### Experiment 1: The RC integrator

This experiment examines the time-domain behavior of the simple RC integrator. Build your integrator using a resistor and capacitor supplied by your TA. You should have an RC time constant of about 0.1ms. 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 $\tau$ 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. For capturing the waveforms you can use

```
>> help get_scope
```

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.
Experiment 2: Time-domain response of follower-integrator

This experiment examines the time-domain response of the follower-integrator circuit. 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 $2k\Omega$ resistor attenuates the signal by a factor of 2 or so. The circuit’s output is buffered by a follower pad so you must set the Follbias knob (pin 5) to about 1V.

Place a subthreshold bias on the $V_\tau$ 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: Due to the function generator assuming 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. But remember that here you also have a resistive divider which will lower the signal amplitude.

Adjust its frequency so that $\tau$ is about 20 per cent of a half-cycle. 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 $\tau$ of the integrator. Is there any difference between the rise and fall times?

**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. Start a decade below the cut-off frequency and take data over at least two decades, doubing 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 $\tau$. How does your value for $\tau$ 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. 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 $\tau$ knob (pin 39) until the output faithfully follows the input. Now decrease the DC level of the input. Capture traces of any weirdness you observe and come up with an explanation. 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.

**EXTRA CREDIT: How slow can you integrate?** (We invite anyone who 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 only acts as an integrator over 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 follower-integrator output will not average to the average level of the input signal. Explain why.

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

5. If you turn it 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. 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 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?

7.4 Next Week

The canonical second order system. Introduction to phototransduction.