University of Utah
Electrical & Computer Engineering Department
ECE 2210 Lab 7

Phases and Filters

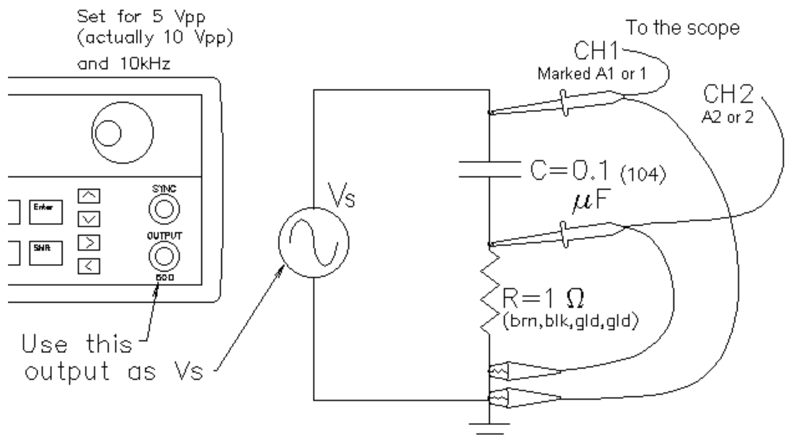
A. Stolp, 2/21/09
Rev 1/12/13

Objectives

1. Observe the phase relationships of current and voltage in a capacitor and an inductor.
2. Make some simple filters and plot their frequency response curves.

Parts: (Parts in **bold** are new to this lab)

1. **1 Ω**, 100 Ω, and 1 kΩ **resistor**s
2. **0.1 µF** (104) & 0.01 µF (103) **capacitor**s
3. Inductor, 2 to 4 mH (probably 3.3mH)



Experiment 1, Current / Voltage phase shifts

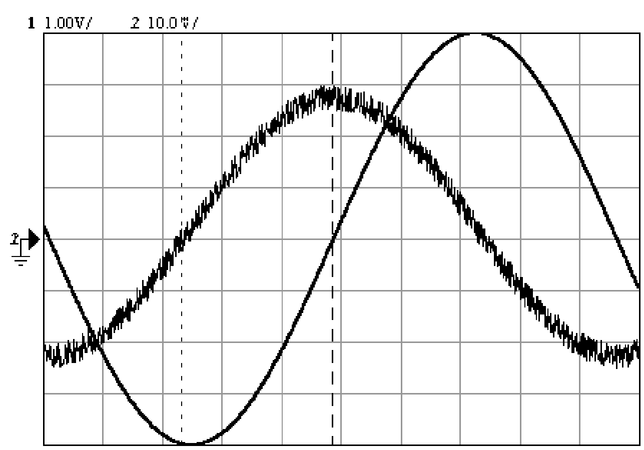
Wire the circuit shown at right, including the scope probes, both set to 1x. Set the signal generator amplitude to 8 Vpp (most will need to be set to 4Vpp to get 8 Vpp) and it's frequency to about 10kHz.

Measure both voltage and current with scope: Turn on the scope and adjust it to see both traces. Notice the small value of the resistor in this circuit (1Ω). This value will have very little effect on the CH1 signal, but will allow the CH2 signal to effectively display the current through the capacitor. Think of the CH2 trace as a measure of the capacitor current. (It may not always look like a nice sinusoid due to noise and scope/circuit irregularities, but try to ignore that in this lab.) You will want to trigger on the cleaner CH1 signal, which may require you to hit the "Trigger" key and the "Source" softkey or something similar. You may also have to set the "Trigger" softkey to "edge".

Note the phase difference of the two traces. Is the current (CH2) leading (to the left of) the voltage?

Phase angle Measurement

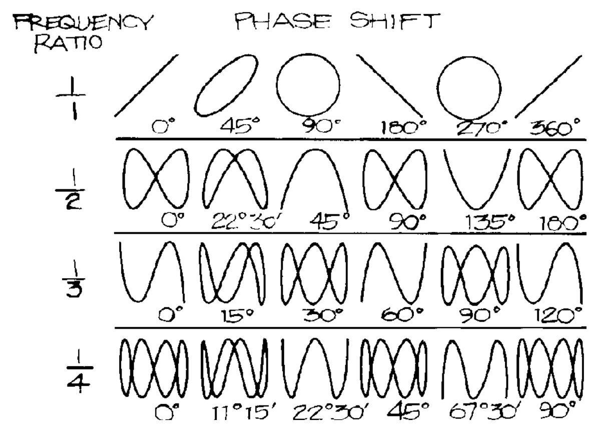
Use the Ch1 position knob to move the tiny ground symbol on the left side of the screen to the center line of the screen. Repeat for the Ch2 position. Refer to the figure at right. Adjust the VOLTS/DIV knobs and the TIME/DIV knob on the scope to get two good, big traces. This may not always be possible, but do the best you can. Find the "Measure" section on the scope. Hit the "Cursors" key, "Cursors" softkey several times until the checkmark is at X1) and adjust the vertical, dotted line with the "Entry ↻" knob



to one of the zero-crossing points on the scope screen. Hit the “Cursors” softkey again to adjust X2 and repeat for the other zero-crossing point. The ΔX is shown at the right side of the screen. Use this measurement and the period (either measured or calculated from frequency) to calculate the phase shift of the current relative to the voltage. Is this 90° as expected?

Circle
Hit the “Horiz” key, “Time Mode” softkey until the checkmark is at “XY“.) In this position the left-right movement of the scope beam is controlled by CH2 rather than scope sweep circuits. CH2 works as normal, making the beam move up and down. If the CH1 and CH2 are both sine waves and are truly 90° out of phase, then you should be able to adjust the VOLTS/DIV knobs to get a perfect circle. You may also have to fine-adjust one channel. Sketch this in your notebook and explain why it’s (almost) a circle. Restore your scope to its normal operation by hitting the “Time Mode” softkey until the checkmark is at “Normal“).

Lissajous (LEE-za-shu) Figures
These figures are generated on the scope screen when two sine waves are used to manipulate the x and y positions of the beam. If the two sine waves have a integer frequency ratio then you’ll see a



stable figure like one of these:

Other frequencies: Adjust the function generator frequency down to 1kHz. Does the phase angle change? Check again at 30 kHz. Also note that the magnitude of the current waveform does change with frequency. Considering that the impedance of a capacitor is inversely proportional to the frequency, is it changing as expected? Return your frequency to 10 kHz.

Repeat with Inductor: Replace the capacitor with your inductor and repeat this entire section, including the detailed phase angle measurement at 10 kHz. Note that the current now lags the voltage by 90°. (You don’t need to explain the circle again, but do everything else including the other frequencies.)

Experiment 2, Simple Filters

The impedance of an inductor is proportional to frequency and the impedance of a capacitor is inversely proportional to frequency. These characteristics can be used to select or reject certain frequencies of an input signal. This selection and rejection of frequencies is called *filtering*, and a circuit which does this is called a *filter*. The bass and treble or equalizer controls on your stereo are frequency filters. So are the tuners in TVs and radios.

You’ve already made a simple filter in the Capacitors lab. We called it a frequency-dependent voltage divider. Almost any circuit where a capacitor or an inductor is part of a voltage divider is a filter. The magnitude of the output voltage is a function of frequency. Look back at the frequency response curve you made in the Capacitors lab.

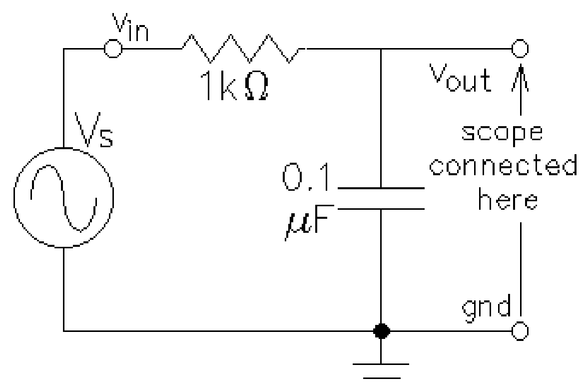
If a filter passes high frequencies and rejects low frequencies, then it is a *high-pass* filter. Conversely, if it passes low frequencies and rejects high ones, it is a *low-pass* filter. A filter that passes a range or *band* of frequencies and rejects frequencies lower or higher than that band, is a *band-pass* filter. The opposite of this is a *band-rejection* filter, or if the band is narrow, a *notch* filter or *trap*. What type of filter did you make in the Capacitors lab? How about the Resonance lab (look at the frequency response curve)?

Filters, like most things, aren't perfect. They don't absolutely pass some frequencies and absolutely reject others. In fact there are large gray areas between pass and reject that make it somewhat arbitrary to say just what *is* and what *isn't* passed. For filters, you measure the pass and reject areas by using a constant magnitude of input signal and varying its frequency. A frequency is considered passed if it's magnitude (voltage amplitude) is within 70% of the maximum amplitude passed, and rejected otherwise. The 70% frequencies are known as *half-power* points, *3-dB-down* points, or *roll-off* points. (Square 0.7 on your calculator to see why they're called half-power points).

For RC (resistor-capacitor) filters, roll-off is where: $R = \frac{1}{\omega_c C}$ $\quad \omega_c = \frac{1}{RC}$ $\quad f_c = \frac{1}{2\pi RC}$

For RL (resistor-inductor) filters, roll-off is where: $R = \omega_c L$ $\quad \omega_c = \frac{R}{L}$ $\quad f_c = \frac{R}{2\pi L}$

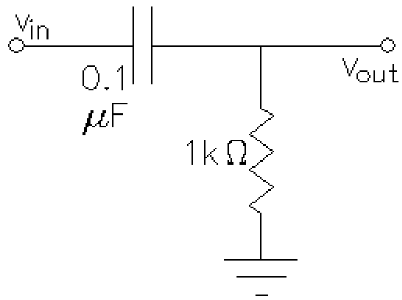
RC low-pass: The filter shown at right is the same one that you built in the Capacitors lab. Look back at that lab now and find the frequency response curve for this filter. Determine what the roll-off frequency (f_c) was from this curve (the frequency where $v_o/v_{in} = .70$).



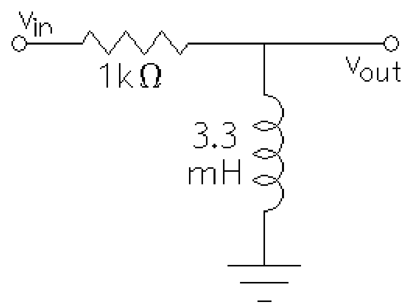
Calculate the theoretical roll-off frequency for this filter and compare this to what you found from the frequency response curve.

Frequency response curves: Calculate the roll-off points for the three filters shown on the next page. You may want to measure the actual value of your inductor and use that value in your calculations instead of 3.3 mH. Your lab TA can show you how to use the HP LCR meter to measure your inductor. If you don't measure your inductor, remember that it probably isn't exactly 3.3 mH when you compare calculations to measurements.

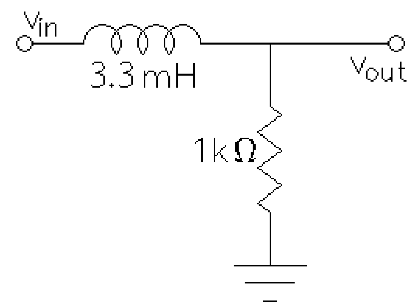
Make one of the RC or RL filters shown on the next page. Use the signal generator to supply v_{in}, and the scope to observe both v_o and v_{in}. This should result in a circuit that looks like the one on the first page of this lab, although the parts will be different. Measure the frequency response of your filter and plot the results on a log plot. You can make your log plot (frequency response curve) in several different ways; use a 1, 3, 10,... pattern of frequencies like you did in the Capacitors lab, use a $\log_2$ pattern like you did in the Resonance lab, use log paper, or use a computer program. In the last two cases you'll tape or paste the plot in your notebook. Be sure to find the roll-off point and compare it to your calculated roll-off frequency.



High-pass RC



High-pass RL



Low-Pass RL

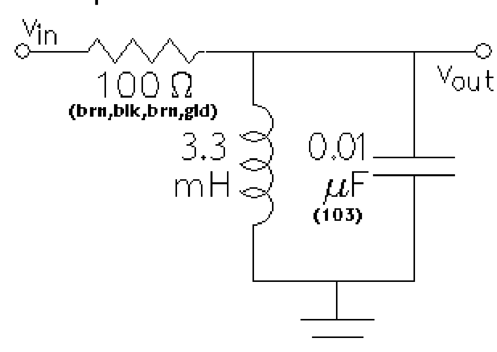
Make one of the other two filters. Confirm that it is high-pass or low-pass as advertised. Find its roll-off point and compare that to your calculated roll-off. You **don't** need to make another curve.

Repeat for the last filter. Again, just confirm that it is high-pass or low-pass as advertised. Find its roll-off point, compare it to your calculation, and **don't** make another curve.

Band-pass filter: Make the band-pass filter shown below. Measure its frequency response and plot the results on a log plot, you'll need quite a few data points. This will be your second curve for this lab. Find the two roll-off point(s) for each, and compare to calculations.

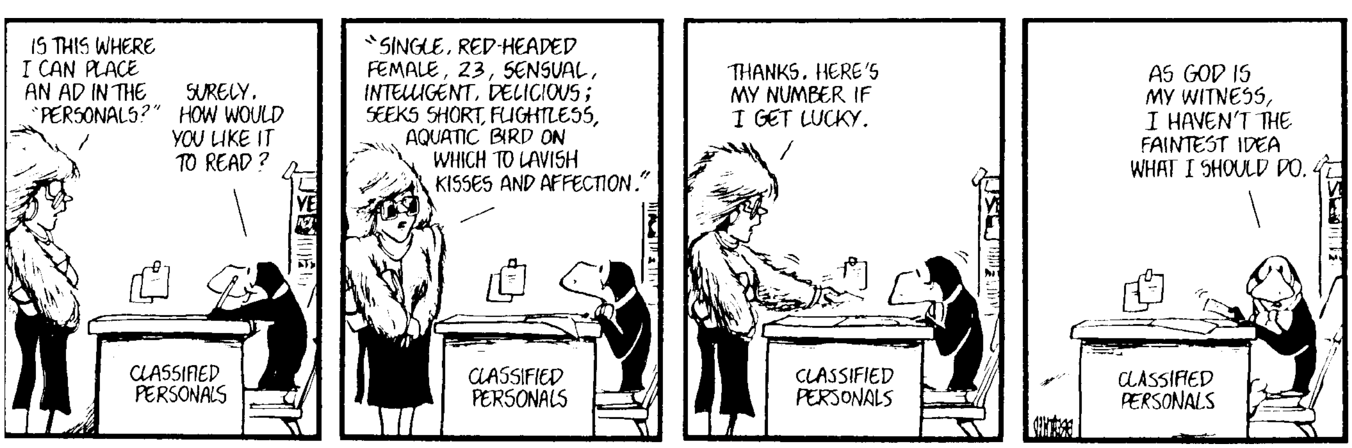
Low frequency roll-off: $f_L = \dfrac{R}{2\pi L}$

High frequency roll-off: $f_H = \dfrac{1}{2\pi RC}$



Conclude

As always, check off and write a conclusion.



University of Utah
Electrical & Computer Engineering Department
ECE 2210 Lab 8
Transients

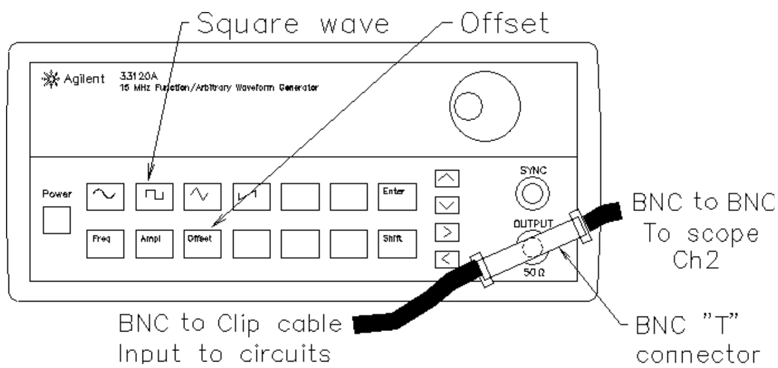
A. Stolp, 11/02/99
rev. 10/24/12

Note : Bring a book to lab that shows second order differential equation solutions (underdamped, critically damped, and overdamped).

Objective
Observe the transient voltages present in RC, RL, and RLC circuits.

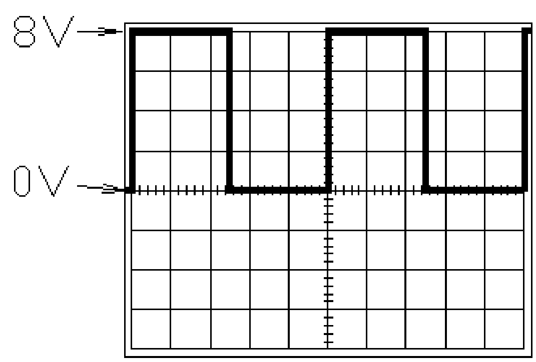
Parts: (Parts in **bold** are new to this lab)
- 0.001 µF (may be marked 102) and **0.22 µF (224) capacitor**s
- 100 Ω (brn, blk, brn), 1 kΩ (brn, blk, red), and **22 kΩ (red, red, org) resistor**s
- Inductor, 2 to 4 mH

Equipment and materials from stockroom:
- Resistor substitution box



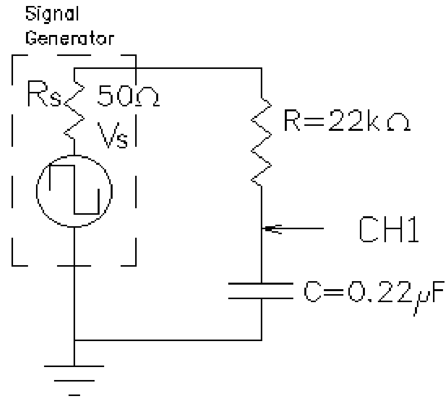
General Setup
Connect a BNC "T" connection to the output of the function generator. Hook one side of the "T": to Ch2 of the scope and the other to a BNC-to-clip lead. This will be the input signal for all the circuits that follow.

Set the HP or Agilent function generator to 8 Vpp (most will need to be set to 4Vpp to get 8 Vpp), square wave (see below). Press the "Offset" button on the function generator and adjust the DC offset to 4 V (usually shows 2 V). Set the function generator frequency to about 10 Hz. This waveform will mimic the action of a switch that is alternately connected to a 8 V source and then ground, with one minor difference. The function generator has 50 Ω output resistance that you should include in your circuit and calculations. It will simply act like an extra 50 Ω resistor in your circuit, located between the switch and the other elements.



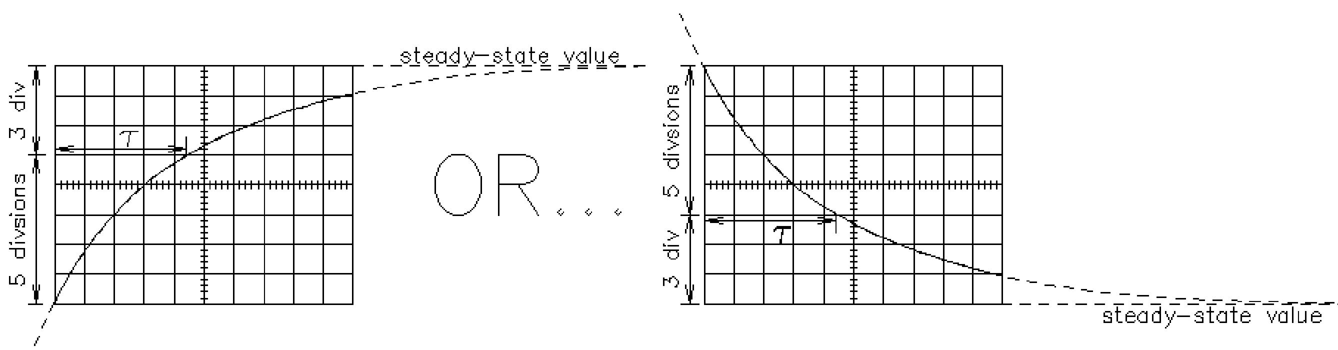
Display this waveform on the scope so that the center is 0 volts and the top is at 8 volts. Set the scope to trigger off this signal (Ch2).

Experiment 1, RC Transient
Construct the RC circuit shown on the next page. Set the scope to view CH1 and adjust it so that you can see two transients with each trace. You should see one transient when the function generator "switches" from 0 to 8 V, and another when it "switches" from 8 to 0 V.



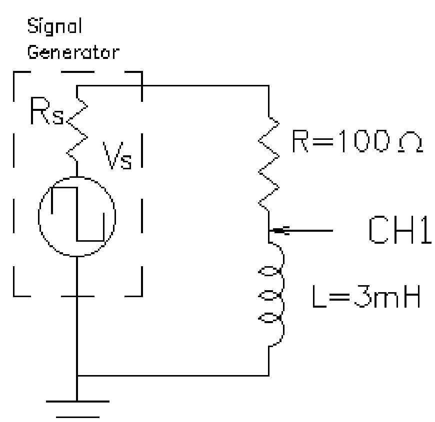
Observe the transient. Does it look like an exponential curve? Does the capacitor voltage ever change from one value to another instantaneously? Draw this transient (v_C) in your lab notebook. Make the vertical axis range of your drawing at least -8 V to +8 V so you can add a drawing of the resistor transient (v_R) later.

Measure the time constant of this RC circuit. Measuring time constants can be a pain, but there is a little trick that you can use on the scope which will let you make this measurement a little faster. It turns out that $e^{-1} \approx 3/8$. Since there are 8 vertical divisions on the scope screen, if you can make the trace fill the screen properly, the trace will cross 5 (8-3) of those divisions in one time constant, see below. Turn the TIME/DIV CCW until you can see the horizontal part of your exponential curve. That will be the steady-state value. Adjust the Vertical Position knob so that this steady-state value is either the top or the bottom line of the screen. Adjust the VOLTS/DIV until the curve covers at least all 8 vertical divisions (don't worry if part of the curve is off the screen). Recheck the steady-state value, then turn the TIME/DIV CW until you can see a good exponential curve. (Note If you push the VOLTS/DIV or the TIME/DIV knobs you get a finer adjustment.) Adjust the Horizontal Position knob so that the trace passes through either the top-left or the bottom-left corner of the screen. Measure the time constant as shown below. You can measure either the charge curve or the discharge curve of the capacitor, but do confirm that the other curve appears to have the same time constant. (If you change the trigger SLOPE on the scope, you will change the visible curve.) Calculate the time constant for this circuit and compare it to your measurement.



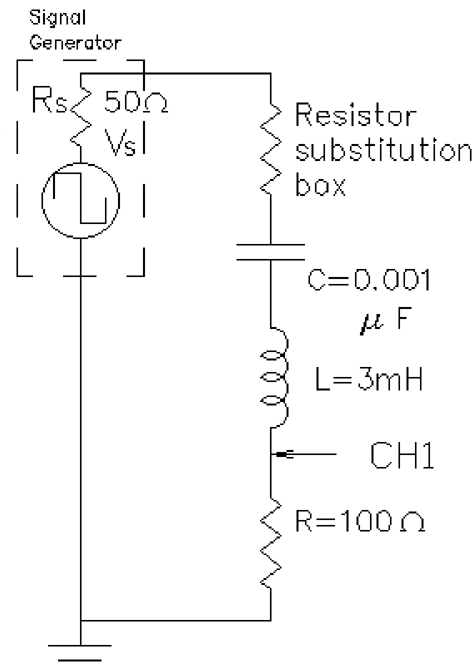
Readjust the scope to see the entire charge or discharge curve like you sketched before you took the time constant measurement. Now swap the positions of the resistor and capacitor. Sketch this new transient (v_R) on your previous sketch. If you added these two traces at each moment in time, would the sum be the input voltage (8 V)? Does the time constant of v_R appear to be the same as v_C?

Experiment 2, RL Circuit



Build the RL circuit shown at right. Turn up the function generator's frequency to about 2 kHz. Repeat all of experiment 1 for the RL circuit, except for the very last part where you switch the part positions. (You may do that for extra points.) Don't be surprised if you see the inductor voltage change instantaneously, in the inductor it's the current which shouldn't change instantaneously.

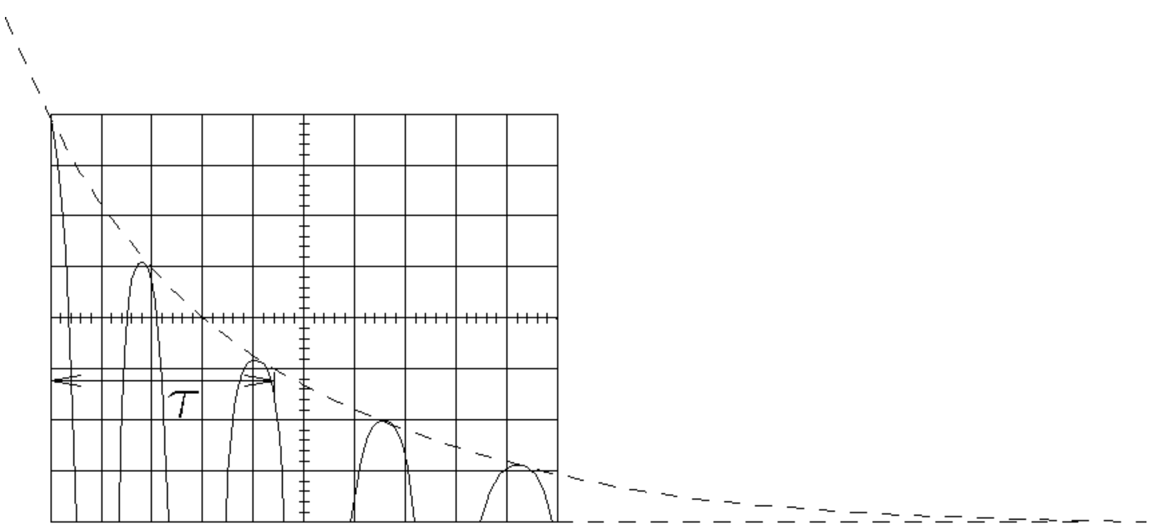
Remember to include the function generator's 50 Ω in your calculations (R=150 Ω for time constant calculation).



Experiment 3, Series RLC Circuit

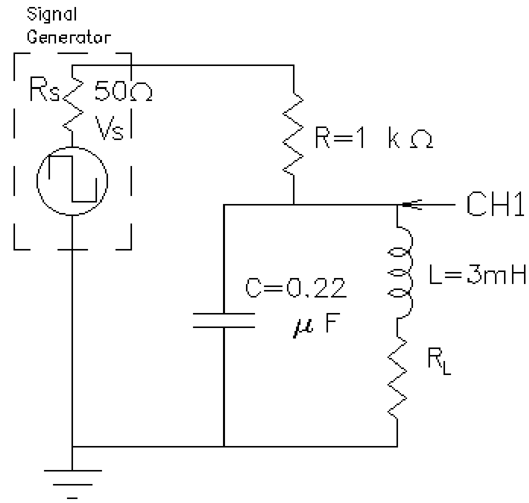
Construct the circuit shown at right. Set the substitution box to 0 Ω (or temporarily short it). Observe the transients. Are they the type of thing you expect? Switch the scope trigger SLOPE to look at other transient. Sketch at least one of them in your notebook. Measure the frequency of the *ringing* (oscillation). Remember that the frequency is 1/T (the period). Try to measure the time constant of the decay, look at the drawing below. Look at the calculations in the appendix and find the calculated values for ω, f, α and τ for this circuit. Compare your measured f and τ to the calculated values

Increase the circuit resistance using the substitution box. At some value of R, you will get critical damping. (Look at your ODE book or a circuits book for a figure showing critical damping.) Adjust the substitution box value and try to find the R that causes critical damping. It turns out to be very difficult to see if the curve is underdamped (ringing), critically damped (one ring) or overdamped (no ringing). It all looks about the same when you're close to the critical damping point. That's OK, do the best you can. I actually want you to see that these curves aren't very different from one another, even though they are calculated very differently. Comment on this in your notebook. Record your R and then add 150 Ω to it to account for the other resistances in this circuit and call the total R_T. Compare this value to the R_T value calculated from theory in the appendix.



Experiment 4, Parallel RLC Circuit

Measure the winding resistance of your inductor (R_L) with an ohmmeter. Construct the circuit shown at right. Note that R_L is part of your inductor and is not added separately. It is shown here so that you can see how it's included in the calculations.

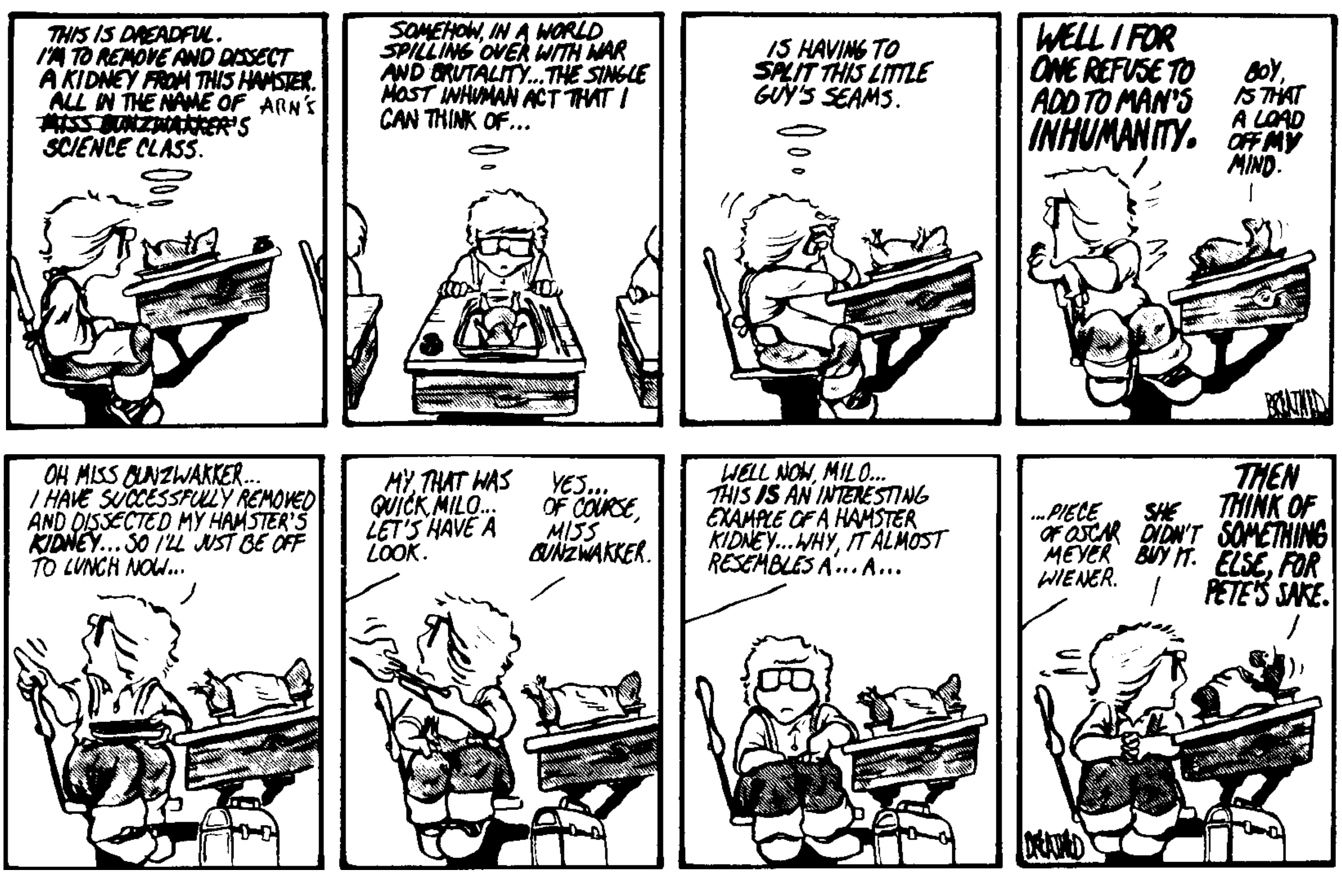


Reduce the function generator frequency to about 200 Hz and observe the transients. Are they the type of thing you expect? Change the scope trigger slope to look at both transients. Sketch one or both of them in your notebook. Measure the frequency of the *ringing* (oscillation) and try to measure the time constant of the decay. Compare your measured f and τ to the calculated values you can find in the appendix.

Conclusion

As always, check off your notebook.

Be sure to comment about how well theoretical calculations describe the actual circuit behaviors. Talk about how well general waveform shapes agree as well as measured numbers.

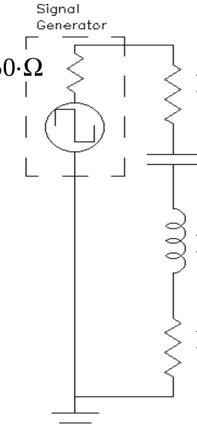


Appendix, Calculations

Series RLC Circuit

$R_T := R + R_s + R_{sub}$

$R_s := 50\cdot\Omega$ $R_{sub} := 0\cdot\Omega$ $C := 0.001\cdot\mu F$ $L := 3.3\cdot mH$ $R := 100\cdot\Omega$



For transient analysis, use the LaPlace s instead of jω for the impedances.
Remember that the LaPlace s = α + jω

Transfer function: $$H(s) = \frac{R}{Ls + R_T + \frac{1}{C\cdot s}} = R\cdot\frac{s}{L\cdot s^2 + R_T\cdot s + \frac{1}{C}} = \frac{R}{L}\cdot\frac{s}{s^2 + \frac{R_T}{L}\cdot s + \frac{1}{L\cdot C}}$$

voltage divider

If you take the denominator of the transfer function and set it equal to zero,
you get the characteristic equation:

Characteristic equation: $$0 = s^2 + \frac{R_T}{L}\cdot s + \frac{1}{L\cdot C}$$

Solve the characteristic equation for s values, using the quadradic equation:

$$s_1 := \frac{\frac{-R_T}{L} + \sqrt{\left(\frac{R_T}{L}\right)^2 - \frac{4}{L\cdot C}}}{2} \qquad s_2 := \frac{\frac{-R_T}{L} - \sqrt{\left(\frac{R_T}{L}\right)^2 - \frac{4}{L\cdot C}}}{2}$$

$$s_1 = -2.273\cdot 10^4 + 5.5\cdot 10^5 j \quad \cdot\frac{1}{sec} \qquad s_2 = -2.273\cdot 10^4 - 5.5\cdot 10^5 j \quad \cdot\frac{1}{sec}$$

s = α + jω , so: $\alpha := \frac{-R_T}{2\cdot L}$ $\alpha = -22727\cdot\frac{1}{sec}$ and: $\omega := \frac{1}{2}\cdot\sqrt{\frac{4}{L\cdot C} - \left(\frac{R_T}{L}\right)^2}$ $\omega = 5.5\cdot 10^5\cdot\frac{1}{sec}$

$f := \frac{\omega}{2\cdot\pi}$ $f = 87.5\cdot kHz$

$e^{\alpha\cdot t}$ is a decaying exponential

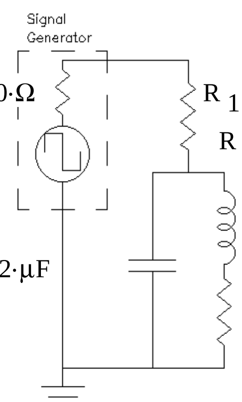
The time constant is: $\tau := -\frac{1}{\alpha}$ $\tau = 44\cdot\mu s$

Compare these to what you measured.

Critcal Damping happens when the part of s under the radical is 0: $\left(\frac{R_T}{L}\right)^2 = \frac{4}{L\cdot C}$ $R_T = \sqrt{\frac{L\cdot 4}{C}} = 3633\cdot\Omega$

Parallel RLC Circuit

$R_s := 50\cdot\Omega$ $R_1 := 1\cdot k\Omega$ $R := 1050\cdot\Omega$ $L := 3.3\cdot mH$ $C := 0.22\cdot\mu F$ $R_L := 5\cdot\Omega$



R_L could be neglected above, but not here

Impedance of C, L, & R_L: $$Z(s) = \frac{1}{C\cdot s + \frac{1}{L\cdot s + R_L}}$$

Transfer function:

$$H(s) = \frac{Z(s)}{Z(s) + R} = \frac{1}{1 + \frac{R}{Z(s)}} = \frac{1}{1 + R\cdot\left(C\cdot s + \frac{1}{L\cdot s + R_L}\right)}$$

$$= \frac{1}{1 + R\cdot C\cdot s + \frac{R}{L\cdot s + R_L}}\cdot\left(\frac{L\cdot s + R_L}{L\cdot s + R_L}\right) = \frac{L\cdot s + R_L}{L\cdot s + R_L + R\cdot C\cdot s\cdot(L\cdot s + R_L) + R}$$

$$= \frac{L\cdot s + R_L}{R\cdot C\cdot L\cdot s^2 + (L + R\cdot C\cdot R_L)\cdot s + (R_L + R)}\cdot\frac{\left(\frac{1}{R\cdot C\cdot L}\right)}{\left(\frac{1}{R\cdot C\cdot L}\right)} = \frac{\frac{1}{R\cdot C}\cdot s + \frac{R_L}{R\cdot C\cdot L}}{s^2 + \left(\frac{1}{R\cdot C} + \frac{R_L}{L}\right)\cdot s + \left(\frac{R_L}{R\cdot C\cdot L} + \frac{1}{C\cdot L}\right)}$$

characteristic equation: $$0 = \left[s^2 + \left(\frac{1}{R\cdot C} + \frac{R_L}{L}\right)\cdot s + \left(\frac{R_L}{R\cdot C\cdot L} + \frac{1}{C\cdot L}\right)\right]$$

Find solutions to the characteristic eq. as above $$s = -\frac{1}{2}\cdot\left(\frac{1}{R\cdot C} + \frac{R_L}{L}\right) \pm \frac{1}{2}\cdot\sqrt{\left(\frac{1}{R\cdot C} + \frac{R_L}{L}\right)^2 - 4\cdot\left(\frac{R_L}{R\cdot C\cdot L} + \frac{1}{C\cdot L}\right)}$$

$\alpha := -\frac{1}{2}\cdot\left(\frac{1}{R\cdot C} + \frac{R_L}{L}\right)$ $\tau = -\frac{1}{\alpha} = 0.342\cdot ms$ $\omega := \frac{1}{j}\cdot\frac{1}{2}\cdot\sqrt{\left(\frac{1}{R\cdot C} + \frac{R_L}{L}\right)^2 - 4\cdot\left(\frac{R_L}{R\cdot C\cdot L} + \frac{1}{C\cdot L}\right)}$ $f = \frac{\omega}{2\cdot\pi} = 5.9\cdot kHz$

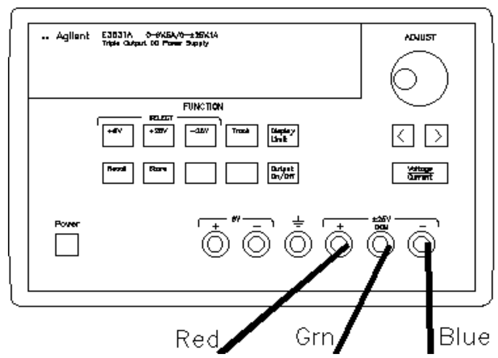
University of Utah
Electrical & Computer Engineering Department
ECE 2210 Lab 9
Control System (Servo)

A. Stolp, 11/09/05
rev, 2/12/13, 10/27/15

Note : Bring a book to lab that shows second order differential equation solutions (underdamped, critically damped, and overdamped) if you're not sure what they look like.

Objective
To see how many of the subjects that you have learned in this class relate to an electro-mechanical control system.

Equipment and materials from stockroom:
- Servo

Experiment
Power supply hookup


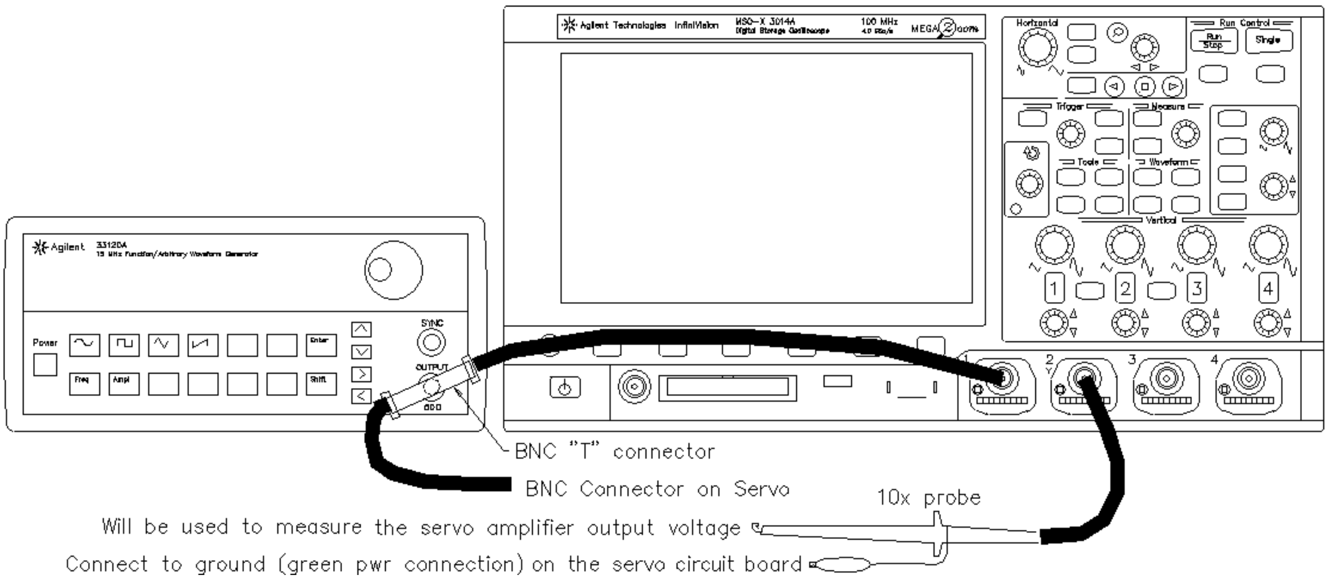
Turn off the power switch on the servo and hook it up to the power supply. Adjust the power supply to provide ± 6V as you did in the first lab. If you've forgotten how to do this, refer back to the lab handout for lab 1. Remember that you may be able to recall the ± 6 V configuration by simply hitting the **Recall** button twice (If no one else changed it in the meantime).

Setup the Servo to minimize friction
In order to get the best results, you will have to make sure the servo isn't running with too much friction. Check the gears and turn them by hand (the red gear is the easiest to turn) to make sure that they are turning freely. The most common cause for binding is the rubber connector between the gear train and the motor position sensor pot. It needs to be pushed onto the pot shaft just the right distance. If it's pushed on the shaft too far, it causes the whitish-clear output gear to rub against the metal frame of the gear train. Too little and it causes the whitish-clear output gear to push the red gear against the white gear. Either way there's too much friction. When you're satisfied that the gears turn smoothly, turn on the power switch on the servo and make sure that it is functioning properly. Turn it back off for now. Make some mention of what you did in your lab notebook.

Setup the Function generator and Scope
Find a BNC "T" connector, look where the wires are hung in the lab or for a small red bin on one of the central tables in the lab. Connect it to the output of the function generator. Then wire the function generator, scope, and servo as shown in the next drawing with two BNC-to-BNC cables and one 10x probe. Connect the scope ground to the big green connector on the circuit board marked "Ground" (where that power supply is connected).

Turn on the function generator and set the **Ampl**itude to 50 mVpp (output will actually be 100 mVpp). Hit the **Shift** key, the **Store** key (shifted **Recall**), turn the knob 'till the display shows "STORE 1", and then hit the **Enter** key. This stores the current configuration of a

100mV, 1kHz sine wave as configuration “1". This configuration (the small, higher-frequency signal) will only be used to determine the gain of the amplifier in the servo. The next configuration will be used to move the servo. Adjust the **Freq**uency to 500 mHz (0.5 Hz), the **Ampl**itude to 500 mVpp (output will actually be 1 Vpp), and set the waveform to a square wave. It needs to be a SQUARE WAVE ! Store this as configuration “2". Make some mention of the configurations in your lab notebook.



Observe how the gain knob affects the response of the servo

Turn down the gain of the servo to minimum (fully CCW). Turn on the servo. It should move back and forth in jerks, making one move every second according to the 0.5-Hz input signal. The input signal is telling the servo to move ~ ± 40° about it’s center position. (These are the “intended positions”.)

Slowly turn the gain knob through its entire range to get an idea of the different types of motion that the servo can make. Return the gain to minimum and observe how little the servo moves and how sluggishly it gets there. Does it overshoot its intended position? Do you think it even reaches its intended position? Slowly turn up the gain. What happens to the motion? Does it get a little more snappy? Does it move further than it did before and thus get closer to its intended position? The low-gain response was slow and had a lot of position error. The response gets much better as you turn up the gain. You can actually hear it get better. Continue to turn up the gain until you start to see (or hear) some overshoot. Just under this point is the optimal gain setting. Turn up the gain further until you get a little ringing (more than one overshoot). In class you’ve learned about the three types of second-order transient responses in terms of overdamped, critically damped, and underdamped. Relate these to the servo outputs you’ve observed at various gains.

Disconnect the function generator, turn up the gain all the way, and turn the input position knob to the center of its range. What is the servo doing now? Can the second-order transient circuits that we studied do that?

Determine minimum gain for oscillation
Turn down the gain very slowly until the oscillation stops, then turn it back up just a hair. Try to get the oscillation started again by turning the “INPUT POSITION” knob a bit. Repeat this until you are satisfied that you’ve found the minimum gain needed for oscillation.

Measure the circuit gain
Disconnect the motor by pulling it’s connector from the circuit board. Note that the circuit board is marked with a + and - at that connector and hook the scope CH2 to the + side. Reconnect the function generator and recall configuration “1" (Hit **Recall**, turn the knob ‘till the display reads “RECALL 1", then hit **Enter**). Observe CH2 on the scope. If it doesn’t show a sine wave, manually turn the red gear and thus the “Motor Position Sensor” until you see a full unclipped sine wave. Check that the scope CH2 is set to match the scope probe (1x or 10x) and then use the scope to find the gain. You may assume the input is 0.1 V_{pp}, so the gain is just $V_{opp}/.1 = 10xV_{opp}$. Disconnect the scope and reconnect the motor.

Determine minimum gain for ringing
Recall the function generator configuration “2". Turn down the gain very slowly and try to find the minimum gain needed for ringing (either direction of motion). Measure the gain as you did above.

Determine minimum gain for single overshoot
Repeat the above procedures to find the minimum gain for a single overshoot (rotates past intended position only once and then turns back and stops). The gain you find now is actually a better estimate of the actual minimum needed for ringing since overshoot is almost always really ringing.

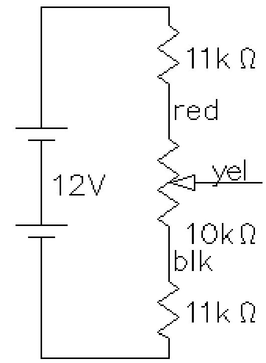
The circuit has a range of gain from min to max of about 1.7 to 133. Confirm this with measurements if you want to.

Compare to calculations
Look at the calculations in the appendix. Do they correspond reasonably well with the cases that you have seen and the gains that you have measured? Notice that although the last one shows oscillation, the frequency is almost 5 Hz. Does your servo oscillate that fast? Does the oscillation continue to grow? The main reason for the discrepancies is that I’ve linearized and simplified the models. The theoretical response is much too fast because I’ve disregarded nonlinearities in the system, particularly power supply limits and amplifier clipping. There simply isn’t enough power to really move that fast. The limits also keep the oscillations from growing without bounds. Additionally, I’ve simply modeled the time delays in the system by using an artificially high motor inductance value. Comment in your notebook.

Find the system block diagram in the appendix. You now have some experience with the gain box of this system and how it affects the system response. You will learn how it works in the last few weeks of this class. The motor and gears transfer function is beyond the scope of this class, although you may well be able to follow its derivation if you’ve had dynamics. You will learn more about these sorts of transfer functions in Mechatronics. The remaining transfer function you will find next. If you look back at the DC or Thevenin labs, you may be able to find the measurements that you need, and can skip taking new ones. Otherwise...

Find Kp, the transfer function of the potentiometers used as position sensors

The "INPUT POSITION" potentiometer translates shaft position into voltage. When the shaft is turned, the voltage on the center lead changes. Hook a voltmeter up to this center lead and circuit ground.

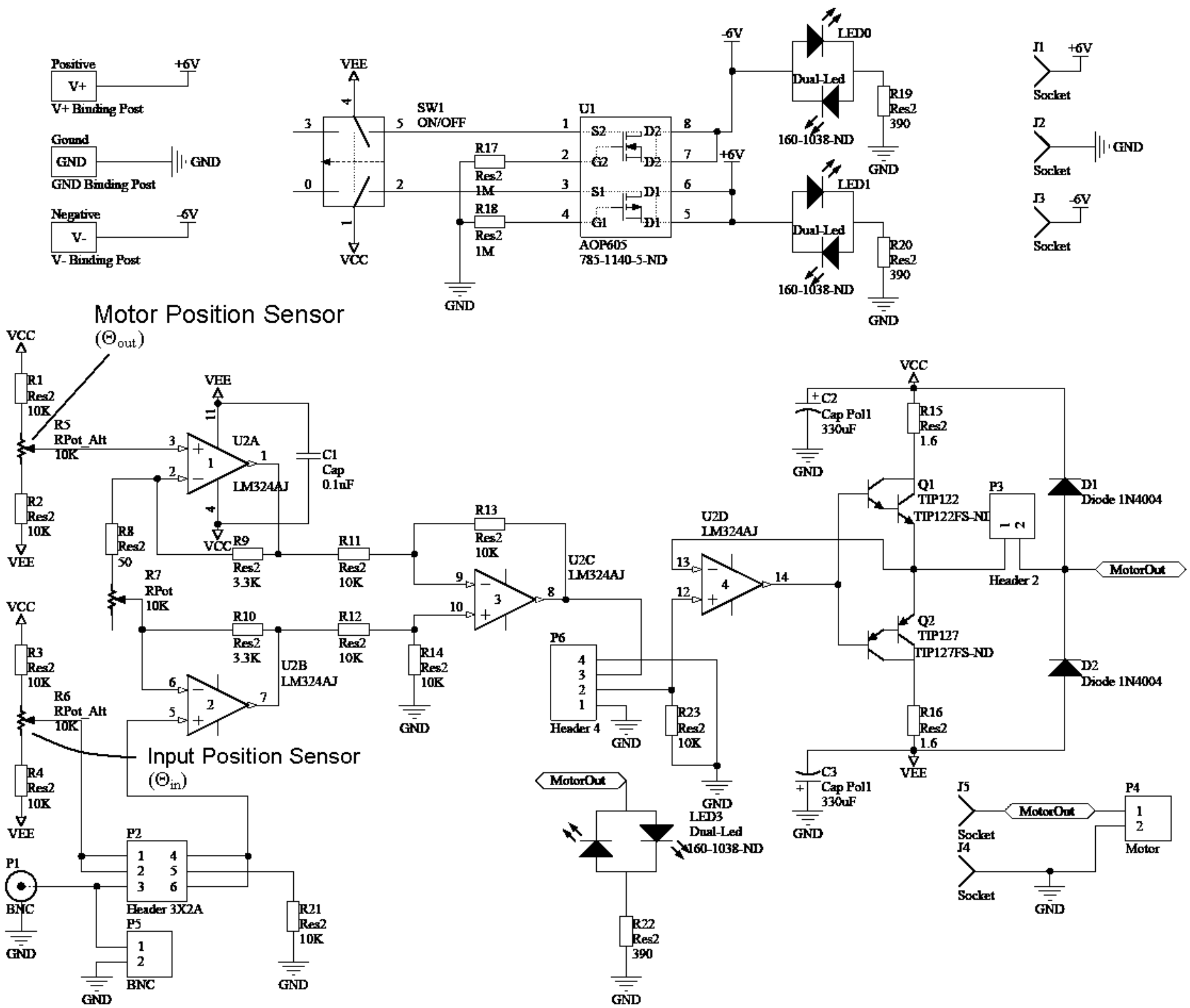


Measure the voltage at the two extremes of the potentiometer rotation. The potentiometer rotates about 270°. K_p is the change in volts per change in angle. Determine K_p as volts/deg and as volts/rad.

Conclusion

Conclude as always. As you've seen, very different kinds of systems can have similar characteristics. That's why learning about transient electrical systems is worth your time and trouble. You will use similar tools to analyze other systems you may even care about.

Servo Schematic



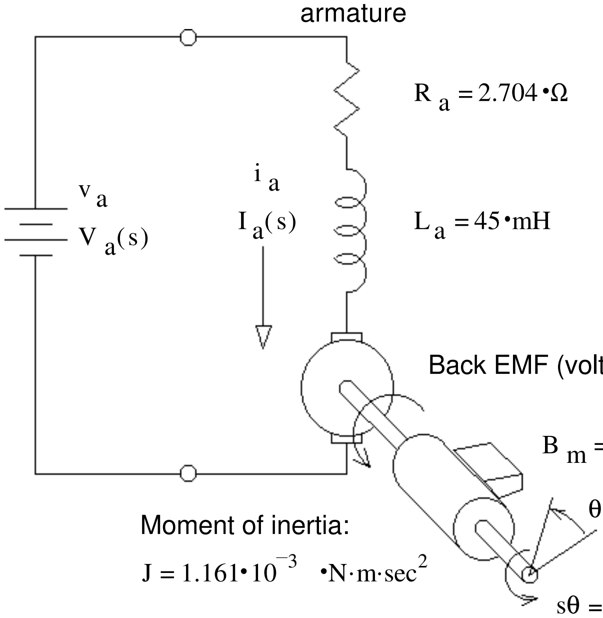
ECE 2210 Appendix: DC permanent-magnet motor & gears

A.Stolp
12/3/04
rev 3/23/06

For motor and gears taken together

Torque constant $K_T = 0.12\cdot\frac{N\cdot m}{A}$ $\quad K_V := K_T \quad$ Voltage constant $K_V = 0.12\cdot\frac{V}{\left(\frac{rad}{sec}\right)}$

armature



$R_a = 2.704\cdot\Omega$ Armature resistance

$L_a = 45\cdot mH$ Armature inductance

Back EMF (voltage generated due to spinning) = $K_V\cdot s\cdot\theta(s)$

$B_m = 0.012\cdot N\cdot m\cdot sec$ Viscous damping factor

θ = angle in radians

Moment of inertia:
$J = 1.161\cdot 10^{-3}\cdot N\cdot m\cdot sec^2$

$s\theta$ = angular speed in radians/sec

$s^2\theta$ = angular acceleration in radians/sec^2

Torque: $$T(s) = J\cdot\left(s^2\cdot\theta(s)\right) + B_m\cdot(s\cdot\theta(s)) = K_T\cdot I_a(s) = K_T\cdot\frac{V_a(s) - K_V\cdot s\cdot\theta(s)}{R_a + L_a\cdot s}$$

$$J\cdot\left(s^2\cdot\theta(s)\right) + B_m\cdot(s\cdot\theta(s)) = K_T\cdot\frac{V_a(s) - K_V\cdot s\cdot\theta(s)}{R_a + L_a\cdot s}$$

$$\left[J\cdot\left(s^2\cdot\theta(s)\right) + B_m\cdot(s\cdot\theta(s))\right]\cdot\left(R_a + L_a\cdot s\right) = K_T\cdot\left(V_a(s) - K_V\cdot s\cdot\theta(s)\right)$$

$$J\cdot s^2\cdot\theta(s)\cdot R_a + J\cdot s^3\cdot\theta(s)\cdot L_a + B_m\cdot s\cdot\theta(s)\cdot R_a + B_m\cdot s^2\cdot\theta(s)\cdot L_a = K_T\cdot V_a(s) - K_T\cdot K_V\cdot s\cdot\theta(s)$$

$$J\cdot s^2\cdot\theta(s)\cdot R_a + J\cdot s^3\cdot\theta(s)\cdot L_a + B_m\cdot s\cdot\theta(s)\cdot R_a + B_m\cdot s^2\cdot\theta(s)\cdot L_a + K_T\cdot K_V\cdot s\cdot\theta(s) = K_T\cdot V_a(s)$$

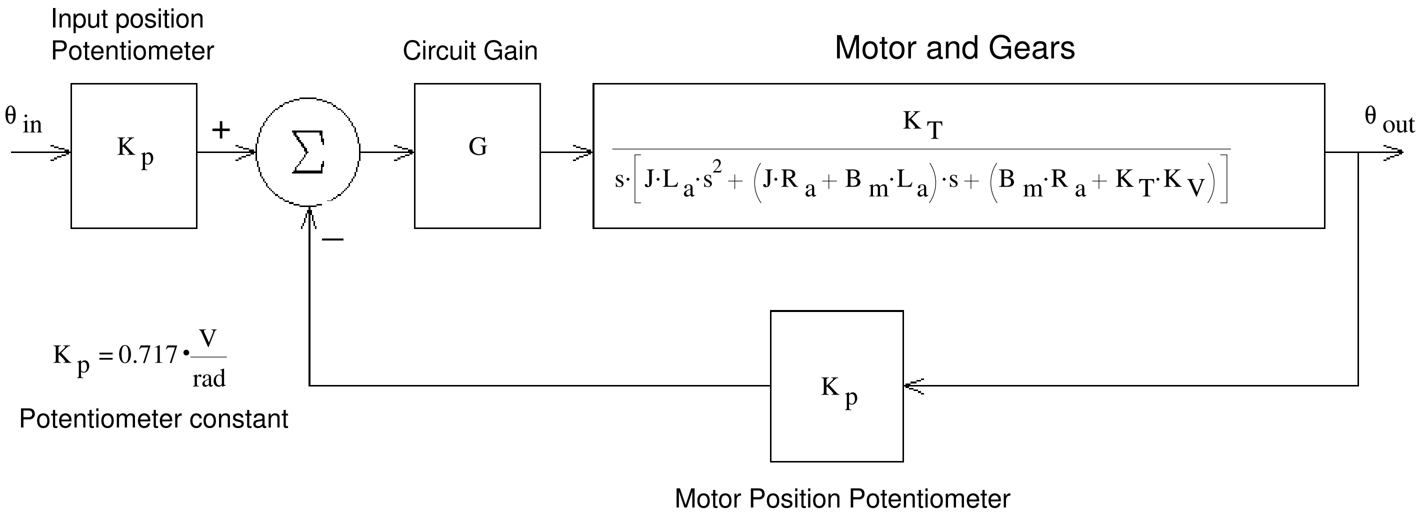
$$\left(J\cdot s^2\cdot R_a + J\cdot s^3\cdot L_a + B_m\cdot s\cdot R_a + B_m\cdot s^2\cdot L_a + K_T\cdot K_V\cdot s\right)\cdot\theta(s) = K_T\cdot V_a(s)$$

$$\left[J\cdot L_a\cdot s^3 + \left(J\cdot R_a + B_m\cdot L_a\right)\cdot s^2 + \left(B_m\cdot R_a + K_T\cdot K_V\right)\cdot s\right]\cdot\theta(s) = K_T\cdot V_a(s)$$

Motor transfer function: $$\frac{\theta(s)}{V_a(s)} = \frac{K_T}{J\cdot L_a\cdot s^3 + \left(J\cdot R_a + B_m\cdot L_a\right)\cdot s^2 + \left(B_m\cdot R_a + K_T\cdot K_V\right)\cdot s}$$

$$= \frac{K_T}{s\cdot\left[J\cdot L_a\cdot s^2 + \left(J\cdot R_a + B_m\cdot L_a\right)\cdot s + \left(B_m\cdot R_a + K_T\cdot K_V\right)\right]}$$

The system block diagram



Overall System transfer function:

$$\frac{\theta_{out}(s)}{\theta_{in}(s)} = K_p\cdot\frac{G\cdot\dfrac{K_T}{s\cdot\left[J\cdot L_a\cdot s^2+\left(J\cdot R_a+B_m\cdot L_a\right)\cdot s+\left(B_m\cdot R_a+K_T\cdot K_V\right)\right]}}{1+K_p\cdot G\cdot\left[\dfrac{K_T}{s\cdot\left[J\cdot L_a\cdot s^2+\left(J\cdot R_a+B_m\cdot L_a\right)\cdot s+\left(B_m\cdot R_a+K_T\cdot K_V\right)\right]}\right]}$$

$$\times\ \frac{s\cdot\left[J\cdot L_a\cdot s^2+\left(J\cdot R_a+B_m\cdot L_a\right)\cdot s+\left(B_m\cdot R_a+K_T\cdot K_V\right)\right]}{s\cdot\left[J\cdot L_a\cdot s^2+\left(J\cdot R_a+B_m\cdot L_a\right)\cdot s+\left(B_m\cdot R_a+K_T\cdot K_V\right)\right]}$$

$$\frac{\theta_{out}(s)}{\theta_{in}(s)} = \frac{G\cdot K_T\cdot K_p}{s\cdot\left[J\cdot L_a\cdot s^2+\left(J\cdot R_a+B_m\cdot L_a\right)\cdot s+\left(B_m\cdot R_a+K_T\cdot K_V\right)\right]+K_p\cdot G\cdot K_T}$$

$$\frac{\theta_{out}(s)}{\theta_{in}(s)} = \frac{k\cdot K_T\cdot K_p}{J\cdot L_a\cdot s^3+\left(J\cdot R_a+B_m\cdot L_a\right)\cdot s^2+\left(B_m\cdot R_a+K_T\cdot K_V\right)\cdot s+K_p\cdot G\cdot K_T}$$

$$\frac{\theta_{out}(s)}{\theta_{in}(s)} = \frac{\dfrac{k\cdot K_T\cdot K_p}{J\cdot L_a}}{s^3+\left(\dfrac{J\cdot R_a+B_m\cdot L_a}{J\cdot L_a}\right)\cdot s^2+\left(\dfrac{B_m\cdot R_a+K_T\cdot K_V}{J\cdot L_a}\right)\cdot s+\dfrac{K_p\cdot G\cdot K_T}{J\cdot L_a}}$$

The characteristic equation: $0 = s^3+p\cdot s^2+q\cdot s+r$

Where: $p := \dfrac{J\cdot R_a+B_m\cdot L_a}{J\cdot L_a}$ $\quad q := \dfrac{B_m\cdot R_a+K_T\cdot K_V}{J\cdot L_a}$ $\quad r := \dfrac{K_p\cdot G\cdot K_T}{J\cdot L_a}$

ECE 2210 DC permanent-magnet motor, p2

for Gain = $G := 1.7$

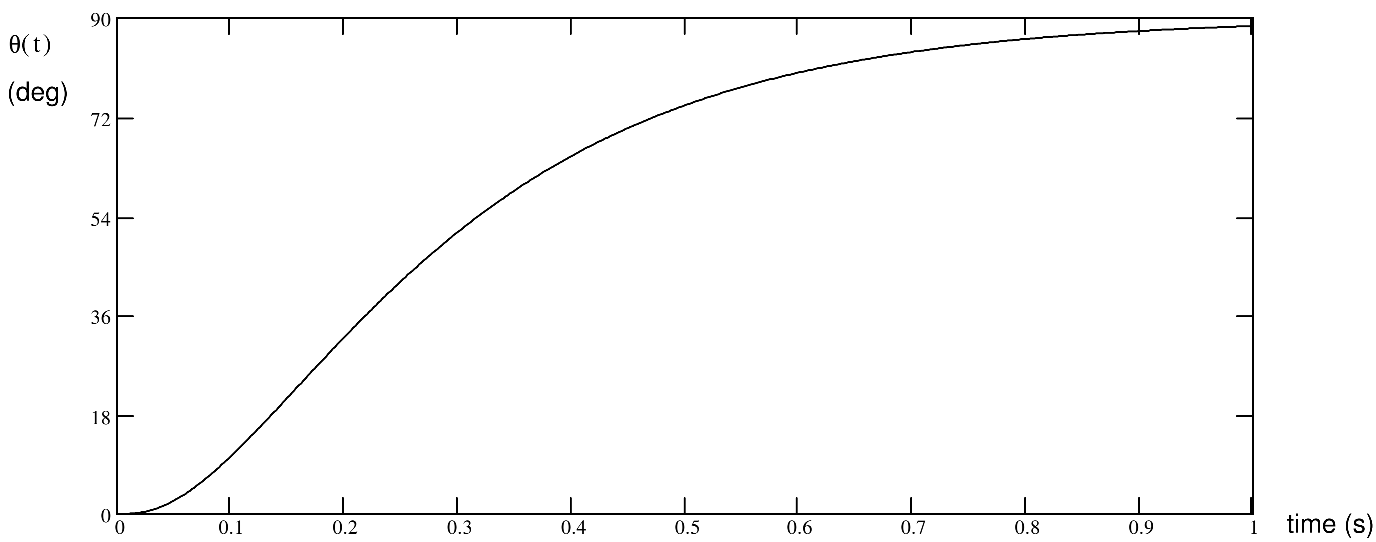
$$r := \frac{K_p \cdot G \cdot K_T}{J \cdot L_a} \qquad a := q - \frac{p^2}{3} \qquad b := \frac{2 \cdot p^3}{27} - \frac{p \cdot q}{3} + r \qquad A := \sqrt[3]{-\frac{b}{2} + \sqrt{\frac{(b)^2}{4} + \frac{a^3}{27}}} \qquad B := \sqrt[3]{-\frac{b}{2} - \sqrt{\frac{(b)^2}{4} + \frac{a^3}{27}}}$$

$$s_1 := (A + B) - \frac{p}{3} \qquad s_1 = -4.83 \cdot sec^{-1} \qquad s_2 := -\frac{A+B}{2} - \frac{A-B}{2} \cdot \sqrt{-3} - \frac{p}{3} \qquad s_2 = -10.494 \cdot sec^{-1}$$

$$\theta_{fin} := 90 \cdot deg \qquad s_3 := -\frac{A+B}{2} + \frac{A-B}{2} \cdot \sqrt{-3} - \frac{p}{3} \qquad s_3 = -55.091 \cdot sec^{-1}$$

$$\begin{pmatrix} D \\ E \\ F \end{pmatrix} := \begin{bmatrix} 1 & 1 & 1 \\ s_1 \cdot sec & s_2 \cdot sec & s_3 \cdot sec \\ (s_1)^2 \cdot sec^2 & (s_2)^2 \cdot sec^2 & (s_3)^2 \cdot sec^2 \end{bmatrix}^{-1} \cdot \begin{bmatrix} -\theta_{fin} \\ 0 \\ 0 \end{bmatrix} \qquad \begin{pmatrix} D \\ E \\ F \end{pmatrix} = \begin{pmatrix} -3.19 \\ 1.655 \\ -0.036 \end{pmatrix}$$

$$\theta(t) := \theta_{fin} + D \cdot e^{s_1 \cdot t} + E \cdot e^{s_2 \cdot t} + F \cdot e^{s_3 \cdot t}$$



for Gain = $G := 14$

$$r := \frac{K_p \cdot G \cdot K_T}{J \cdot L_a} \qquad a := q - \frac{p^2}{3} \qquad b := \frac{2 \cdot p^3}{27} - \frac{p \cdot q}{3} + r \qquad A := \sqrt[3]{-\frac{b}{2} + \sqrt{\frac{(b)^2}{4} + \frac{a^3}{27}}} \qquad B := \sqrt[3]{-\frac{b}{2} - \sqrt{\frac{(b)^2}{4} + \frac{a^3}{27}}}$$

$$s_1 := (A + B) - \frac{p}{3} \qquad s_1 = -61.962 \cdot sec^{-1} \qquad s_2 := -\frac{A+B}{2} - \frac{A-B}{2} \cdot \sqrt{-3} - \frac{p}{3} \qquad s_2 = (-4.227 - 18.796j) \cdot sec^{-1}$$

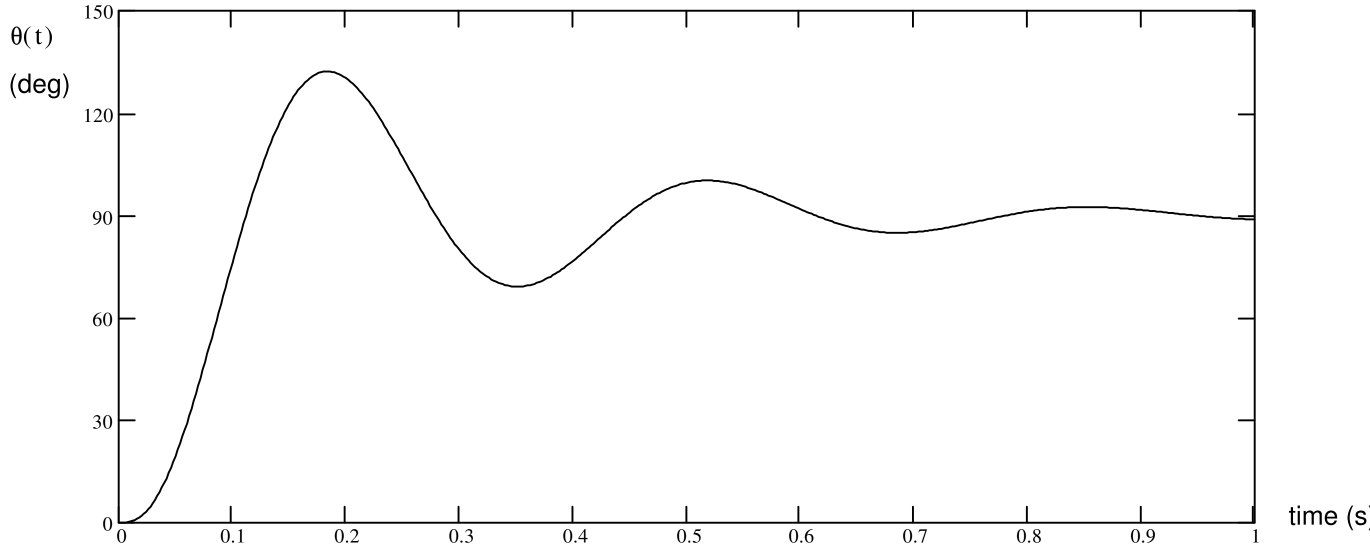
$$\theta_{fin} := 90 \cdot deg \qquad s_3 := -\frac{A+B}{2} + \frac{A-B}{2} \cdot \sqrt{-3} - \frac{p}{3} \qquad s_3 = (-4.227 + 18.796j) \cdot sec^{-1}$$

$$\begin{pmatrix} D \\ E \\ F \end{pmatrix} := \begin{bmatrix} 1 & 1 & 1 \\ s_1 \cdot sec & s_2 \cdot sec & s_3 \cdot sec \\ (s_1)^2 \cdot sec^2 & (s_2)^2 \cdot sec^2 & (s_3)^2 \cdot sec^2 \end{bmatrix}^{-1} \cdot \begin{bmatrix} -\theta_{fin} \\ 0 \\ 0 \end{bmatrix} \qquad \begin{pmatrix} D \\ E \\ F \end{pmatrix} = \begin{pmatrix} -0.158 \\ -0.706 - 0.419j \\ -0.706 + 0.419j \end{pmatrix}$$

$$\theta(t) := \theta_{fin} + D \cdot e^{s_1 \cdot t} + E \cdot e^{s_2 \cdot t} + F \cdot e^{s_3 \cdot t}$$

Plot on next page

ECE 2210 DC permanent-magnet motor, p3



G = 14, Decaying Oscillation (ringing)

for Gain = $G := 40$

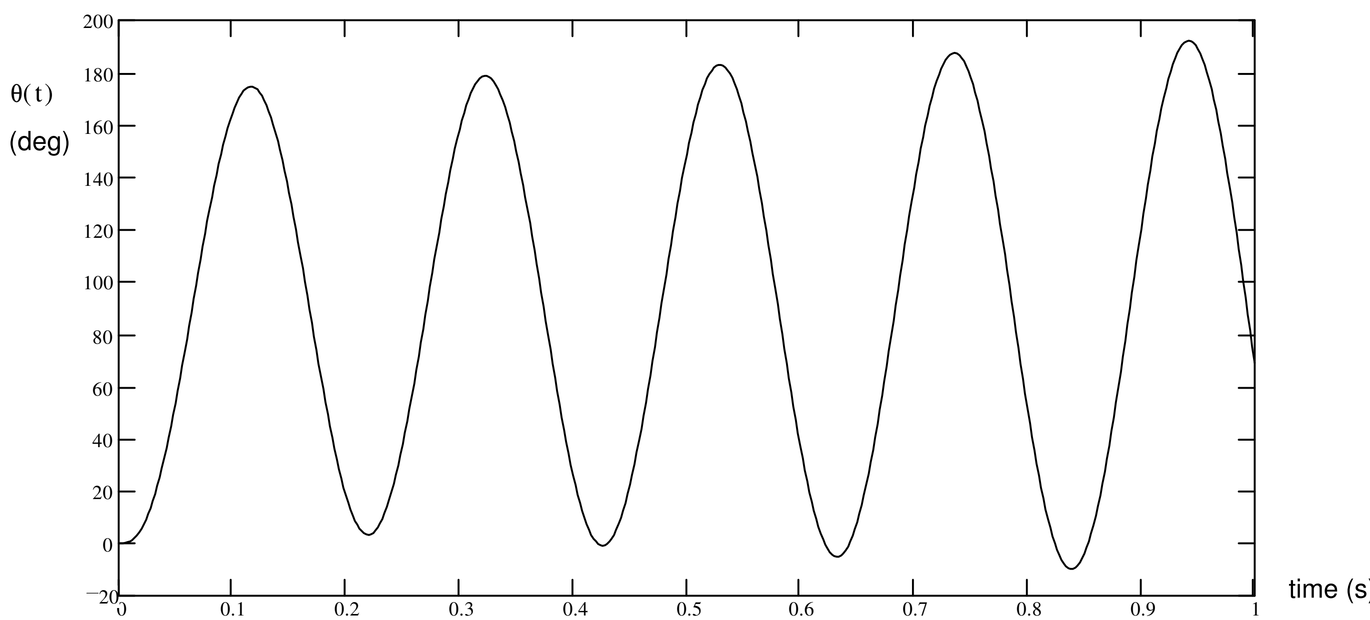
$$r := \frac{K_p \cdot G \cdot K_T}{J \cdot L_a} \qquad a := q - \frac{p^2}{3} \qquad b := \frac{2 \cdot p^3}{27} - \frac{p \cdot q}{3} + r \qquad A := \sqrt[3]{-\frac{b}{2} + \sqrt{\frac{(b)^2}{4} + \frac{a^3}{27}}} \qquad B := \sqrt[3]{-\frac{b}{2} - \sqrt{\frac{(b)^2}{4} + \frac{a^3}{27}}}$$

$$s_1 := (A + B) - \frac{p}{3} \qquad s_1 = -70.87 \cdot sec^{-1} \qquad s_2 := -\frac{A+B}{2} - \frac{A-B}{2} \cdot \sqrt{-3} - \frac{p}{3} \qquad s_2 = 0.227 - 30.448j \cdot sec^{-1}$$

$$\theta_{fin} := 90 \cdot deg \qquad s_3 := -\frac{A+B}{2} + \frac{A-B}{2} \cdot \sqrt{-3} - \frac{p}{3} \qquad s_3 = 0.227 + 30.448j \cdot sec^{-1}$$

$$\begin{pmatrix} D \\ E \\ F \end{pmatrix} := \begin{bmatrix} 1 & 1 & 1 \\ s_1 \cdot sec & s_2 \cdot sec & s_3 \cdot sec \\ (s_1)^2 \cdot sec^2 & (s_2)^2 \cdot sec^2 & (s_3)^2 \cdot sec^2 \end{bmatrix}^{-1} \cdot \begin{bmatrix} -\theta_{fin} \\ 0 \\ 0 \end{bmatrix} \qquad \begin{pmatrix} D \\ E \\ F \end{pmatrix} = \begin{pmatrix} -0.243 \\ -0.664 - 0.278j \\ -0.664 + 0.278j \end{pmatrix}$$

$$\theta(t) := \theta_{fin} + D \cdot e^{s_1 \cdot t} + E \cdot e^{s_2 \cdot t} + F \cdot e^{s_3 \cdot t}$$



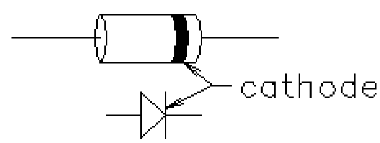
G = 40, Growing Oscillation

University of Utah
Electrical & Computer Engineering Department
ECE 2210
Diodes & Transistors

A. Stolp, 11/23/99
rev,11/26/12

Objective
Observe the workings of diodes and transistors. Since this lab is primarily build and observe. Your lab notebook should be a record of those observations.

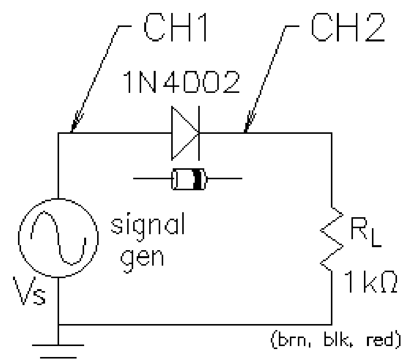
Parts: (Parts in **bold** are new to this lab)
- **56 Ω** (grn,blu,blk), **510 Ω** (grn,brn,brn),100 Ω (brn,blk,brn),1 kΩ (brn,blk,red), 22 kΩ (red,red,org), and 100 kΩ (brn,blk,yel) resistors
- 0.22 μF (224) and a 47 to 220 μF capacitor (use this cap where schematic calls for or 100 μF)
- **1N4002 or 1N4004 diode** (black plastic)
- **Red, green, and yellow LEDs**
- **1N4734 5.6 V zener diode** (gray) (may use 1N4730)
- **2N3904 transistor**



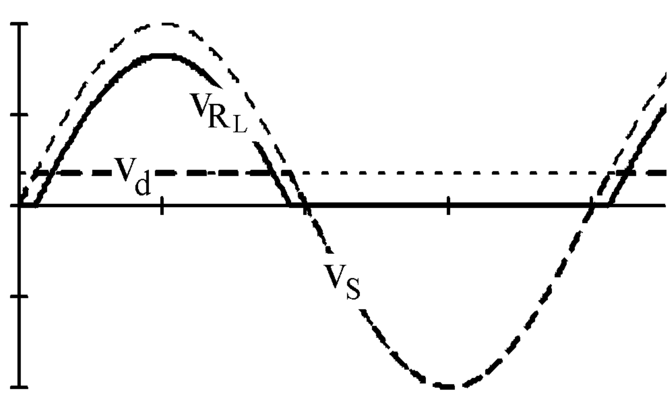
Equipment and materials from stockroom:
- Servo

Note: You will build lots of circuits in this lab—some quite complex. Build them carefully, or you'll spend too much time troubleshooting. Make your observations and sketches quickly so you can move on. Your sketches don't have to be perfect, just fast.

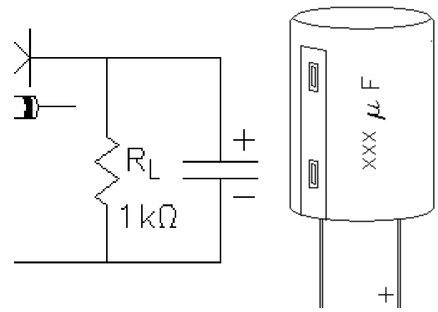
Experiment 1, Rectification
Half-wave rectifier: Wire the circuit shown at right. The 1N4002 parts are *power* diodes and they have large leads. These leads can be hard to get into the breadboard holes. If you look closely at the lead ends, you'll see that many are cut with a wire cutter that leaves a beveled end. If you line the bevel up with the holes that are connected inside the board, they go in a lot easier. Otherwise, wiggle and twist them as you push them in the board.



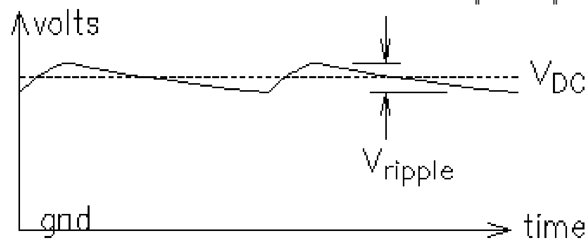
Hook up the scope, and make sure that both scope inputs are set to "DC" coupling. Turn on the signal generator. Set the signal generator amplitude to 4 Vpp (which will actually give 8 Vpp) and it's frequency to about 60 or 100 Hz sine wave. Observe and sketch the two waveforms that you see (v_S and v_L). Note the half-wave rectification. The load voltage is now "DC", although it's not very "pure".



Place a 47 to 220 µF capacitor in parallel with the load resistor (**remember the capacitor polarity—you don't want to blow up the capacitor**). Observe and sketch the filtering effect of the capacitor. The load voltage is better than it was, but it's still not great. The DC voltage still has significant "ripple". Measure the peak-to-peak voltage of this ripple. Add a second capacitor in parallel with the first. Comment about how the added capacitance effects the ripple.



Notice that the capacitors also distort the input voltage during the short time that they charge. The current during this time is quite high and the distortion is caused by the voltage drop across the 50 Ω output resistance of the signal generator. The same thing happens in power supplies, although the currents are usually higher and the resistances are usually lower. Remove the capacitors.

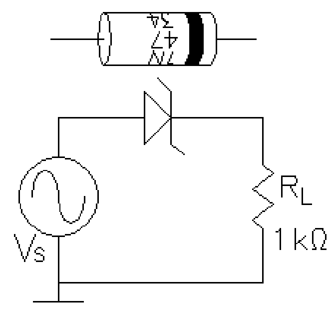


Change the input to a triangular wave. Observe the waveforms.

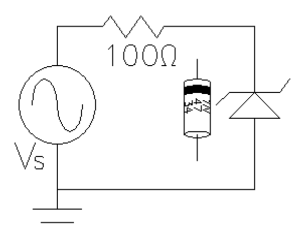
Experiment 2, Other Types of Diodes

Zener Diodes

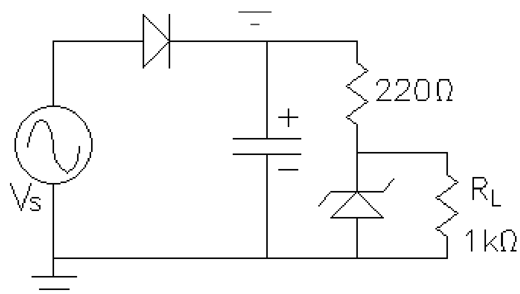
Set the signal generator amplitude to 8 Vpp (which will actually give 16 Vpp). Replace your diode with the 1N4734 zener diode as shown. Notice that the while the diode works exactly like a regular diode in the forward direction, it also lets current flow in the reverse direction when the input is more than 5.6 V negative. The voltage across R_L is proportional to that current. Sketch v_S and v_L you see on the scope.



Change the circuit to that shown at right (notice the resistor is a different value). Now the waveform is *clipped* at about +5.6 V and -0.7 V. A zener diode has a specific reverse breakdown voltage and is often used as a voltage reference or regulator. Sketch v_S and v_D you see on the scope.

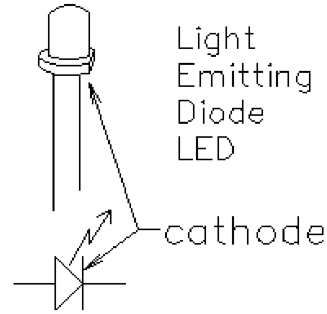


The circuit at right shows a more normal use of a zener diode as a voltage regulator. You DO NOT have to make this circuit. This is called a "shunt" regulator. As long as there is always a reverse current through the zener, the voltage across the zener will be regulated to about 5.6 V. Turn off the function generator.

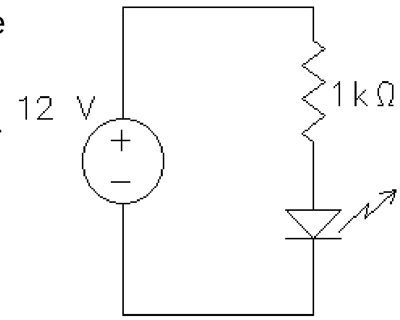


Light Emitting Diodes

Make the circuit on the next page using the DC power supply and one of the LEDs (red, green, or yellow). Notice the resistor is 1kΩ again. Calculate the LED current assuming the voltage drop across the LED is about 2 V. This is a pretty good assumption for LEDs. In fact, to design an LED circuit you usually make this 2 V assumption and calculate a resistor value which will allow about 10 to 20 mA to flow



through the LED. Never just hook an LED up directly to a voltage source--unless you *want* to let the smoke out. Measure the actual LED and resistor voltages and calculate the actual current flow in the circuit. Compare this to what you calculated from your assumption. Try the other two LEDs in this circuit and measure the voltage drop across each.

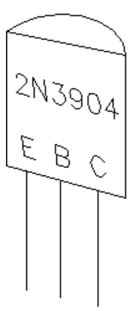


Experiment 3, Transistors

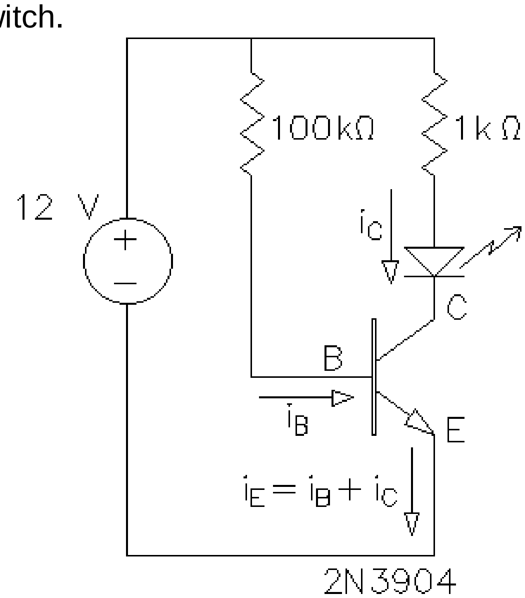
Transistor switch

A transistor is a nifty little device which controls current flow. It has three terminals--the *base*, the *collector*, and the *emitter*. The current flow from the collector to the emitter (through the transistor) is controlled by the current flow from the base to the emitter. You can think of this as the base current controlling the collector current. A small base current can control a much larger collector current. They are related by a simple factor, called *beta* (β). For a given base current, the transistor will allow β times as much collector current. Big power transistors usually have a β between 20 and 100. For little signal transistors, β is usually between 100 and 300. Because a small current can control a large current a transistor can be used as an *amplifier*. That is, it can make a larger signal from a smaller one. (A signal is a voltage or current that carries information. In the lab we usually simulate signals with sine waves.)

A transistor can also be used as a current controlled switch. When there's no base current, it acts like a switch that's off. When there *is* a base current, it's on. When it's on there are two possibilities. 1. The transistor is in control and limiting the collector current to β times the base current (βI_B). Or, 2. the transistor does the best it can to let βI_B current flow but circuitry outside the transistor won't let that happen. In that case the transistor turns on completely, like a closed switch and *other* elements in the circuit limit the collector current to less than β times the base current. In the first case the transistor is said to be operating in the *active region* because the transistor is in *active* control of the current. In the second case the transistor in the *saturated* region and is working like a switch.

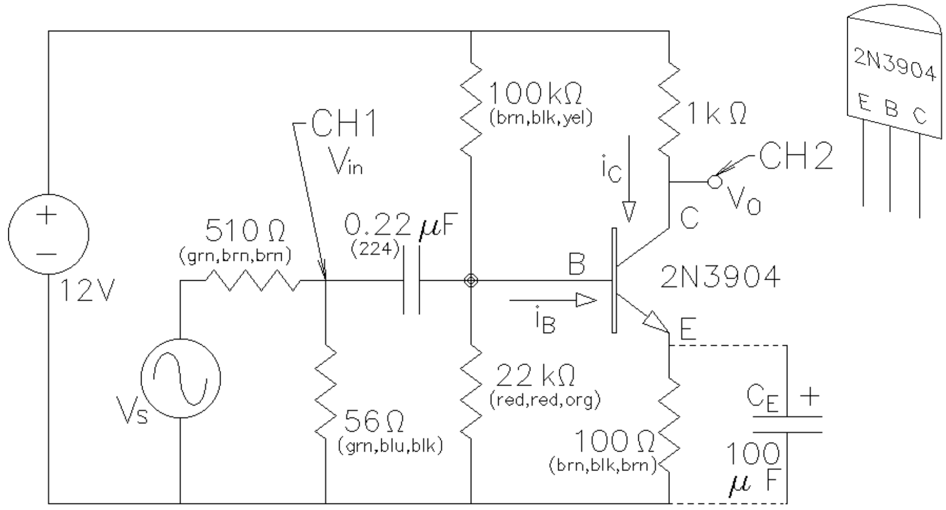


Find your 2N3904 transistor. It's a small black part with three leads. The leads may be labeled on the part as E, B, and C or else look at the drawing to the left. E, B, and C denote the **E**mitter, **B**ase, and **C**ollector. Expand your LED circuit to the one shown at right. Note the symbol for the transistor, and it's E, C, and B labels.



The LED should be lit, indicating that the transistor is "on". Disconnect the 100 kΩ resistor and the transistor turns "off", reconnect it and the LED lights again. Repeat this several times to convince yourself that the base current controls the collector current. Notice now that the base current flows through a 100 kΩ resistor whereas the collector current flows through only a 1 kΩ resistor. The base current (the controller) is roughly 1% of the collector current (which it controls)! A very small current controls a much larger current.

Transistor amplifier
In the final circuit we'll use a transistor to amplify a voltage signal. I won't try to explain the circuit. I just want you to build it and see that it works.



Construct the circuit shown at right. Use the function generator as v_s and set the frequency to about 5 kHz. DO NOT connect the 100 µF capacitor at this time.

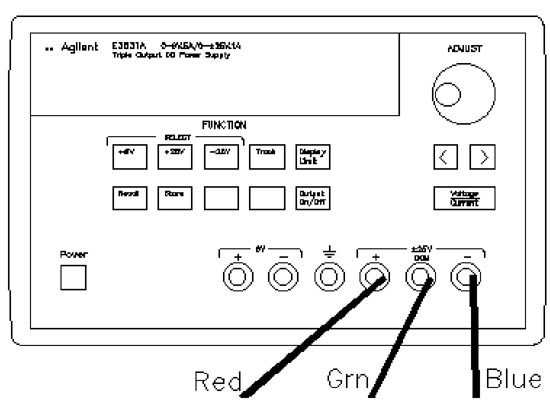
Please note that the 510 Ω and 56 Ω resistors are NOT part of the amplifier. They are needed because the function generator output (V_{pp}) cannot be turned down low enough for this circuit. Together they constitute a voltage divider which reduces v_s by about a factor of 10. The actual v_{in} of the amplifier circuit is measured where CH1 is connected.

Increase (or decrease) the function generator (v_s) V_{pp} so that the output signal ($v_{o,}$ CH2) shows just a little clipping. Clipping is a form of distortion that "chops-off" some of the top and/or bottom of the output waveform. Now turn the input down somewhat so that the output looks good, with no visible distortion or clipping. The output voltage is a combination of the AC output signal and a DC *bias* voltage. You may have to adjust the vertical position knob on the scope or set the CH2 scope coupling to "AC" in order to see the signal on the scope. Measure the input (v_{in}) and output (v_O) signal voltages (AC peak-to-peak). Calculate the circuit voltage *gain* (gain = v_o/v_{in}). It should be about 10. Notice that the output signal is inverted with respect to the input. This is normal for this circuit. Sometimes the gain is reported as a negative number to indicate this inversion (-10).

Add the 100 µF capacitor (47 µF or 220 µF will also do) and repeat the previous step. The gain should be much bigger now (I measured 200) but is not so easy to predict. It is now dependant on variations within the transistor. Also notice that the output has a more distorted appearance (top is more rounded, bottom is sharper). Nevertheless, you must admit that this is a pretty remarkable gain for such a simple circuit. I hope you can see where such a circuit might come in handy.

Diodes and Transistors in the Servo

Look at the Servo and at its schematic diagram (last page of this lab). Find LED0 and LED1 which are actually two LEDs in the same package, hooked up in opposite directions. They light green if the power is correct or red if backwards. Look at the schematic and calculate how much current should flow through these LEDs.



Turn off the power switch on the servo and hook it up to the power supply. Adjust the power supply to provide ± 6V as you did in the first lab. If you've forgotten how to do this, refer back to the lab handout for lab 1. Remember that you may be able to recall the ± 6 V configuration by simply hitting the **Recall** button twice (If no one else changed it).

Find the 390 resistors, R19 and R20 on the servo circuit board. Measure the voltage across R20 and calculate the actual current through LED1. Measure the voltage across LED1 (the easiest way to this is to place one lead of the voltmeter on the Positive input terminal and the other on the end of R20 closest to LED1). Compare your measurement to the 2-V assumption.

Find diodes D1, & D2 near the motor disable jumper (between the big electrolytic capacitors and the transistors. Find them on the schematic as well. Why are these diodes there? Find the bi-color LED3. It lights red with one direction of current, green with the opposite direction, and yellow with an AC current. Why do you get yellow If the current is AC? What is the purpose of R22? Turn the input position pot back and forth quickly to see the LED light red and green.

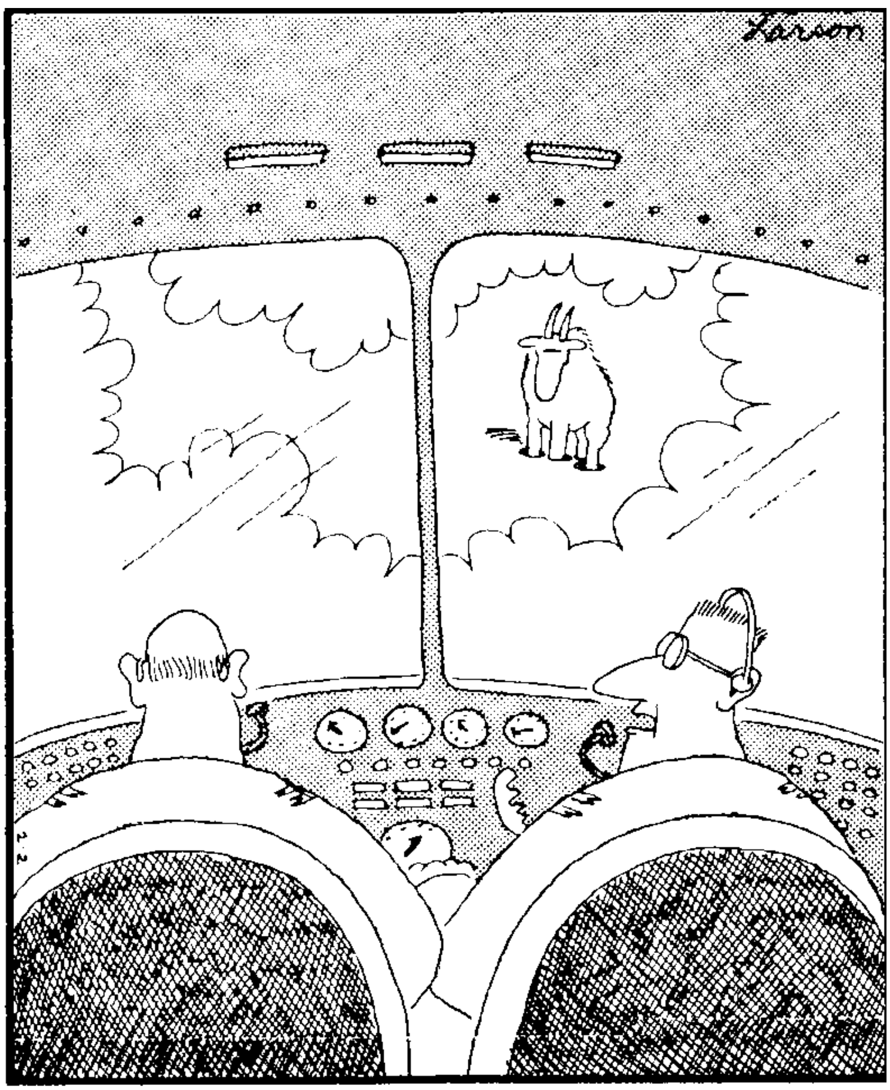
Find the transistors Q1, & Q on the schematic. What is the purpose of these transistors and why are there two? Why do you suppose the actual transistors are attached to the pieces of aluminum? Turn the input position pot to about midway. Touch both aluminum heatsinks at the same time. Now turn the red gear by hand until you feel significant resistance from the motor. Hold this position until you feel one of the transistors heat up. (You may have to turn up the gain.) Let go of the red gear and then turn it the other way. Does the other transistor heat up? Why do the transistors heat up? Why does the heating depend on which direction the motor is trying to turn?

Conclusion

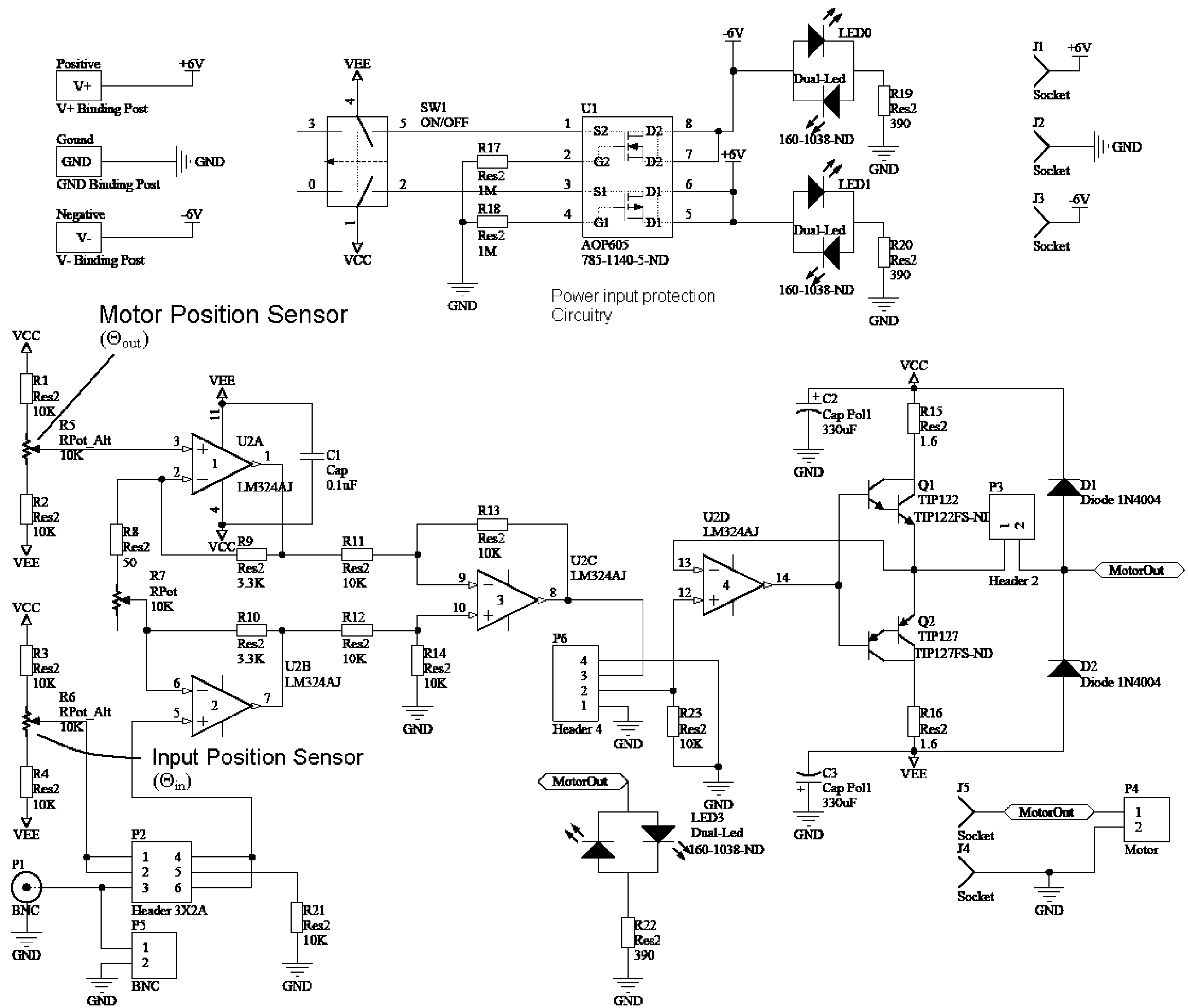
Page back through this lab and just look at all the circuits that you built today. You've come a long way this semester, and you should pat yourself on the back. I hope that it wasn't too painful. The transistor that you used in this lab is known as an "active device". Active devices are the basis of *electronics*.

Keep the schematic on the last page of this lab. You will refer to it again in the next lab.

As always, get your notebook checked off and write a conclusion.



"Say . . . What's a mountain goat doing way up here in a cloud bank?"

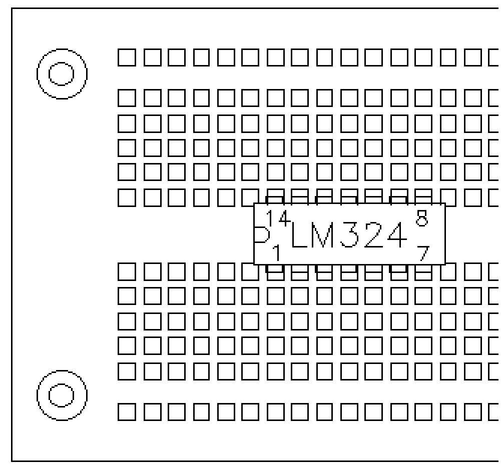

Motor Position Sensor
(Θ_{out})
Input Position Sensor
(Θ_{in})
Power input protection
Circuitry

University of Utah
Electrical & Computer Engineering Department
ECE 2210
Operational Amplifiers

A. Stolp, 11/28/01
rev, 11/28/12

Note: Bring the Op-amp handout from class and the servo schematic from lab 11. Bring the Control Systems lab handout (Lab 9) if you don't remember how to measure the voltage gains of the servo and you didn't document it well enough in your lab notebook.

Objective
To explore some of the more common uses of operational amplifiers, also known as op-amps.

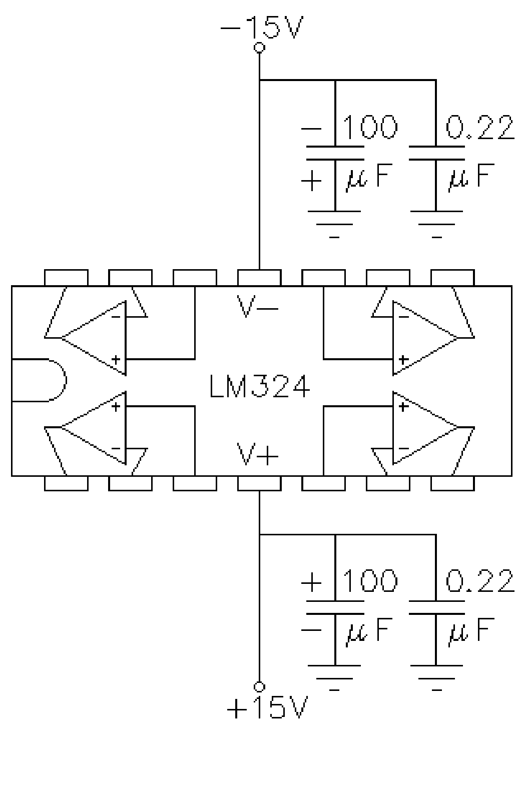


Parts:
- Resistors of your choice in the 100 Ω to 1 MΩ range.
- two 0.1 to 0.22 µF (224) capacitors
- two 47 µF to 100 µF capacitors
- **LM324 or TL084 (better) quad operational amplifier**
- Breadboard and wires

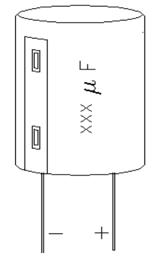
Equipment and materials from stockroom:
- Servo

Experiment
Plug the LM324 IC (Integrated Circuit) into the breadboard so that it spans the little center ditch. The notch and/or white band should be on the left and the writing on the IC should be right-side-up. The leads of the IC are numbered around in a CCW direction, starting in at the lower-left corner.

The op-amps inside the LM324 are shown at right. This one IC contains four complete op-amps. All are powered by the same two power input terminals, V+ and V-. To get both +15 and -15 V from the power supply, first push and hold the "Track" button for at least 1 second. Then push the "+25V" button and adjust the voltage to 15V. With tracking turned on the "-" output will "track" the "+" output and automatically be set to -15V. Hook up +15 V to the V+ pin of the IC and -15 V to the V- pin. Look carefully at the drawing, don't hook the power up backwards-- it's easy to do because the V- pin is on top (which is counter-intuitive). The V- and V+ connections are power connections. DO NOT confuse them with the signal inputs to the op-amps (labeled - and +).



Most op-amp circuits won't work right unless the op-amp is powered with both + and - power supplies. This can be inconvenient, but using op-amps with single-sided supplies is tricky. REMEMBER this! One common mistake people make with op-amps is trying to use them with a single power supply.



The power supply's ground will be the ground for all your circuits and should be hooked to the breadboard somewhere, but is not hooked up to the op-amp directly.

Finally, some capacitors are a good idea. They suppress noise and oscillation problems that can cause you headaches later. The values are not critical, and you can often get by without using them at all, but I do recommend hooking some up as shown. Don't connect the electrolytic capacitors backwards! Remember that they have + and - leads.

If it doesn't work...

1. Use a voltmeter to check the voltages at the power pins.
2. Check other connections, especially ground.
3. Try another op-amp within the LM324.
4. Have your circuit checked by the TA and if it's OK, replace the IC with another. ICs can be damaged, especially if the power is hooked up backwards.

Voltage follower

Find the voltage follower circuit in the Operational Amplifiers handout. Choose one of the four op-amps in the LM324 and build a voltage follower. (That constitutes one wire hooked from the output to the - input.) Hook the signal generator in the bench up to the + input of the same op-amp. Hook the CH1 of the scope up to the output and hook CH2 to the input. Hook all grounds together. Set up the signal generator to produce a sine wave at about 1 kHz and observe the op-amp output with the scope. Adjust the signal generator if necessary so you see a good output. Observe the input signal and determine if the input and output are the same (Make sure that the "cal" knobs on the scope are all in the full CW position). Draw the circuit in your notebook and record the measurements which confirm that this circuit works as expected.

Noninverting Amplifier

Find the noninverting amplifier in the Operational Amplifiers handout. Design and build an amplifier with a voltage gain of about 11. Use resistors of your choice, but use values in the 100 Ω to 1 MΩ range (I suggest R_1 = 10 kΩ and R_f = 100 kΩ). Test this circuit like you did the voltage follower, only now you're looking for the amplitude of the output voltage to be 11 times bigger than the amplitude of the input. If the output waveform shows clipping, turn down the amplitude of the input signal. Draw the circuit in your notebook (with the parts values that you used) and record the measurements which confirm that this circuit works as expected.

$\underline{v_a \approx v_b}$

Move the CH1 scope channel from the op-amp's output to its - input. Now CH2 should be hooked to the + input and CH1 to the - input. Confirm that these two signals are practically the same, as expected. Return CH1 to the output.

Clipping

Turn up the amplitude of the input signal until the output waveform shows clipping both top and bottom. This is a non-linearity of the amplifier. Sketch the clipped waveform in your notebook. Use the scope to measure the maximum positive and maximum negative voltages available from the op-amp (the clipping levels, also called the "rail" voltages). Look at the two op-amp inputs like you did in the previous paragraph. Notice that the two inputs are not the same anymore and that whenever they are noticeably different, the output is at either its positive or negative limit. Sketch these two waveforms (the two op-amp inputs inputs) in your notebook. Return the scope connection to the output and turn down the amplitude of the input signal so the output is about 20 Vpp.

Slew

Turn up the frequency of the input signal until the output looks like a triangle wave instead of a sine wave (It will be a little smaller too). What you're seeing is the maximum rates (up and down) at which the op-amp is able to change its output voltage. In this case it isn't fast enough to keep up with the sine wave. Sketch the slewing waveform in your notebook. If you turn down the amplitude of the input signal you can make the output look like a sine wave again. Why? Turn the frequency back down to around 1 kHz.

Inverting Amplifier

Build the Inverting amplifier discussed in the Operational Amplifiers handout. Use resistors of your choice to create an amplifier with whatever gain you want, but choose values in the 100 Ω to 1 MΩ range. (I suggest a gain $\leq$10 or you won't be able to get a small enough signal from the 33120 function generator to keep the circuit from clipping.) Draw your circuit in your lab notebook. Apply an input signal and confirm that the output is now inverted (up-side down, or 180° out of phase) with respect to the input. Measure the voltage gain and compare to expectations.

One More Op-amp Circuit

Build another one of the circuits discussed in the Operational Amplifiers handout (any one you want). If you make the summer, make it with just two inputs and either use the "+5V" output of the DC supply as your second input or check-out a second signal generator. If you make the differentiator, I suggest C = 0.22 µF (224) capacitor R_{in} = 10 kΩ. If you make the integrator, I suggest C = 0.22 µF (224) capacitor R_{in} = 1 kΩ and R_f = 100 kΩ.

Draw your circuit in your lab notebook. Devise tests which will measure the important properties of your circuits. (Does the circuit do what it should do and is the output the right amplitude for the given input?) Compare your measurements to calculated expectations.

Servo

Look at the servo schematic (attached to last week's lab). It uses at least two of the circuits shown in the Operational Amplifiers handout. Determine which circuits and label them on the big schematic (or a new one from your TA or website). The LM324 on the servo contains 4 op-amps. The output pin numbers are 1, 7, 8, & 14 (see the first figure on page 1 of this lab). Look at the schematic and determine which op-amp is lower-left, which is the lower-right, which is the upper-left, etc. Label them on the schematic as LL, LR, UL, and UR. Tape the schematic into your lab notebook (probably as a foldout).

The last op-amp, connected to the transistors, has a voltage gain of 1. The first three op-amps have a variable gain, depending on the position of the gain knob. The two voltage inputs to the circuit are the center connections of the two position sensor potentiometers. If you consider the input to be the difference of these two voltages and the output to be the motor voltage. Determine the minimum voltage gain from the component values given on the schematic and the gain expressions given in the op-amp handout. Determine the maximum gain.

Turn the gain pot on the servo to minimum gain (fully CCW). Turn on the function generator and reduce the signal amplitude until it shows 50 mVpp (actually output is 100 mVpp). Find lab 9, the Control Systems lab in your lab notebook. That should tell you how to measure the gain of the servo. If you didn't document it well enough in your lab notebook, you may want to refer to the Control Systems lab handout. Use that method now to measure the minimum gain. Turn the gain pot on the servo to maximum gain (fully CW). Measure the maximum gain. Compare your measured values to those you calculated from the schematic.

Extra Credit

Build and test one or two more of the circuits in the Operational Amplifiers handout. Each circuit that you build, test, and document is worth up to 10 extra-credit points.

Conclude

Check off. Write a normal conclusion in your notebook. Comment on how some of these circuits might be used. You may not be able to see how they could *all* be used, but I expect you to be able to describe uses for at least a couple of them.

OK. That's it. Lab is over. I hope you got something out of it all. If you're an ME student, you'll see many more electrical and op-amp circuits in your Mechatronics labs, only those labs will be more fun, especially if you learned the basics in this lab.