2.737 Mechatronics
Laboratory Assignment 2: Analog Feedback Systems

Assigned: 3/1/06
Pre-lab due: 3/8/06 in class
Reports due: week of 3/13/06 in checkoffs
Reading: Feedback system notes Chapter 6, Apex Evaluation Kit specs

1 Overview

In this lab you will experiment with designing and stabilizing power op amp circuits. These devices are used to drive loads requiring significant power, such as motors, solenoids, deflection coils, speakers, etc. We will use two types of loads. The first is just a power resistor driven directly by the power op-amp. The second is an inductor driven in a closed-loop current-controlled mode. This second design will be implemented by using a second low-level op-amp to drive the power op-amp. You will need to model the system to design an appropriate controller. Then you will test this connection in the lab to measure its performance. You will design this low-level controller and build it on a section of the protoboard in your nerd kit.

2 Power Amplifier Connections

Please read this section carefully before making any circuit connections, and before applying any power to the circuit.

In this laboratory, we will take a closer look at the power amplifier that powered the servomotors in Laboratory 1. We study using this power op amp to drive loads requiring more power than is available from a low-level op-amp such as the 741 (which is limited to about 10 mA max output current). To this end you will work with an Apex PA-21 power operational amplifier mounted on their EK-21 evaluation board. Data sheets for this amplifier and for the evaluation kit are included with this handout. Please read these data sheets in order to familiarize yourself with the amplifier characteristics. **Note: The most important datum on this sheet is that the amplifiers have an absolute maximum of ±25 volts. Irreversible damage will occur above this level. The supplies in the lab can provide more than ±30 volts and thus are capable of destroying the amplifier. Therefore, before shutting off or turning on the supply *always* set it to 0 volts on both sides.**

Referring to the EK-21 data sheet, we have installed only one of the two possible PA-21 units. In the installed PA-21, we will only use the A side. The B amplifier is left unconnected. On the A side, the following components have been installed: $R_6 = R_7 = R_{14} = 0\ \Omega$ (jumpers), $R_1 = R_5 = 10\ \text{k}\Omega$ (gain setting resistors), $C_5 = C_{12} = 100\ \mu\text{F}$ (low-frequency bypass capacitors), and $C_4 = C_{11} = 0.1\ \mu\text{F}$ (high-frequency bypass capacitors) All other components are omitted. Terminals 1 and 3 are brought out on green and red wires, respectively. The board ground plane is also brought out on a black wire for connection on the low-power side. On the high-power side, we

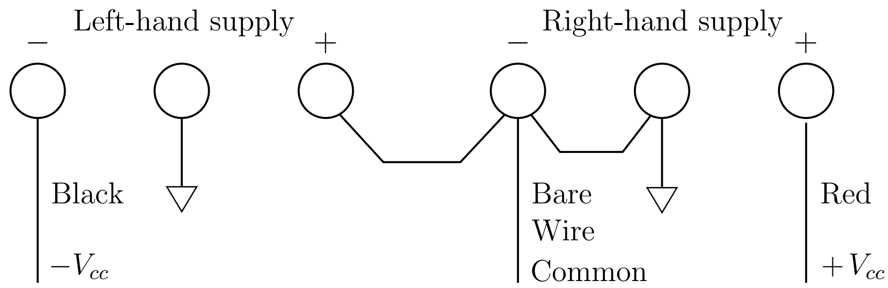

Figure 1: Amplifier/supply connections

have brought out the power supplies with $+V_{cc}$ on a red wire, $-V_{cc}$ on a black wire, and common on an unisulated wire. The amplifier output A is brought out on a yellow wire along with another connection to common on a black wire.

Supply connections: In the following, we refer to the two 0–30 volt supplies available on the Tektronix power supply. The unit also has a 5 volt supply which we do not use in this lab. The supplies in the lab have been furnished with jumpers and connected for series operation. Please keep the supply in this configuration throughout the laboratory. In this mode, the right-hand voltage control sets the voltage output for both supplies. *Never set the power supply to more than ±17 V. Also carefully check for the correct polarity with a voltmeter when the amplifier is first attached to the supply.* As connected, the right-hand supply provides $+V_{cc}$ at its positive terminal, and the left-hand supply provides $-V_{cc}$ at its negative terminal. Common is taken from the jumpered center connections (the negative terminal of the right-hand supply and/or the positive terminal of the left-hand supply).

The current limits for each supply are set independently, and should be initially adjusted to about the vertical position. If in testing the CC light glows, this means that the current limit is being reached. If there is not a fault condition, and you are doing testing which requires the higher current, you may gradually increase the current limit setting on the supply until the CC light goes out. Whenever you are about to turn on the supply, first adjust both voltage controls to zero. Set the right-hand meter to monitor voltage. Set the left-hand meter to measure current. Then power up the supply. At this point you may gradually increase the supply voltage, and watch for any sudden increase of the supply current. (Occasionally switch the right hand meter to monitor current in that leg of the supply, then switch back to voltage as you increase the voltage setting.) Also, always have an oscilloscope connected to the amplifier output, and watch for any oscillations or latching behavior. If everything looks OK, then you can increase the supply voltage up to the desired ±17 volt level. (The reason for choosing this voltage is that it is comfortably below the amplifier's absolute maximum rating of ±25 volts.) One final note: The current loop will not work properly until the power amp supply approximately exceeds the protoboard supply, due to common-mode limitations of the PA-21 amplifier. **Thus, do not power up the protoboard until the power amp is at the final ±17 volt level.** The amplifier should be wired to the supply as shown in Fig. 1.

3 Assignments

1. **Resistive load:** Carefully connect the amplifier to the supply as described above. Use a 10 Ω, 25 W power resistor as the load in a non-inverting gain of two connection. The circuit you build should appear as shown in Fig. 2. The 10k resistors shown are soldered-in on the amplifier board. We have also soldered in a pair of 1 MΩ resistors to provide the input current of the amplifier under conditions where you have not connected its inputs. However for present purposes, you can simply ignore these resistors. Use your protoboard to interface the signal generator through a BNC connector to the input of the power amplifier. The power resistor is provided for you on the amplifier terminal strip.

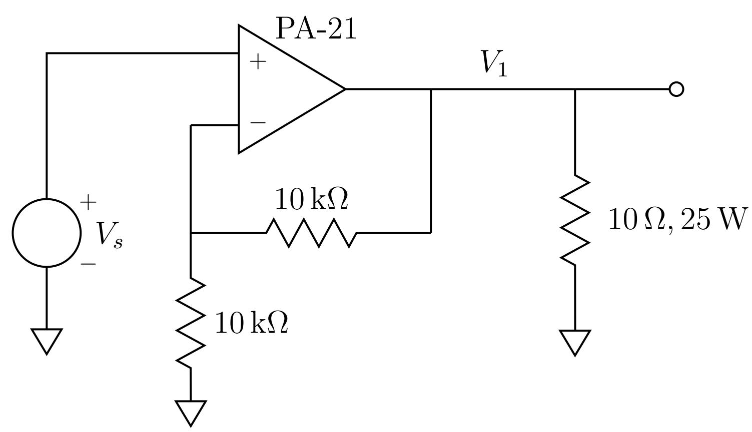

Figure 2: Amplifier with resistive load. The 10k resistors shown are soldered-in on the amplifier board.

For this circuit, we want you to predict and measure the closed-loop dynamic response of the amplifier. Use the data sheet for the PA-21 to determine an appropriate model for the amplifier. Use this model in a block diagram for the connection to predict the loop crossover frequency, phase margin, and closed-loop step- and frequency-responses. Use Matlab to simulate your system, and plot the expected step response.

Now in the lab, measure the closed-loop step and frequency responses. Try to explain any discrepancies between what you predict and what you measure in the lab. In this and subsequent sections, be sure that your measurements are "small-signal" in that the amplifier is responding linearly. In order to test whether you are in this regime, decrease the input signal amplitude until the output scales linearly with the input. What departures from linearity can you observe with both step and sine inputs? As one specific, can you observe the effects of the amplifier slew-rate limit?

2. **Inductive load, voltage drive:** Now we will use the amplifier to drive an inductive load as shown in Fig. 3. Each station has an inductor which has been constructed from a small power transformer. Please keep each device at its original station. Do not move these around between stations! For the greatest consistency, you may want to use the same station for all your critical tests, but since the inductors are nominally identical, you are free to use other stations and assume the inductors are matched. The purpose of this portion of the lab is to develop an electrical model for the inductor which can be used to design a closed-loop current-controlled system. Specifically, in this section, we would like to measure the transfer

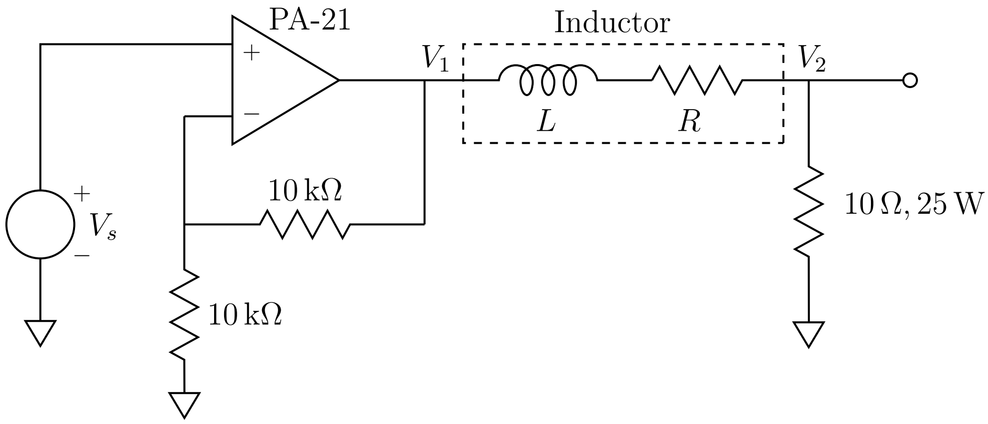

Figure 3: Amplifier with inductive load.

function from V_1 to V_2 as a function of frequency. This transfer function is then embedded in the current-controlled loop described in the next section.

The inductors we are using are made by cutting the excess leads off some small power transformers. Since these transformers have an iron core with no air gaps, they thus provide a large inductance in a relatively small volume. However, they also thus begin to show saturation effects at relatively low currents. To stay in the linear mode of operation, you will need to keep the currents on the order of ± 0.1 A maximum. However, the nonlinear behavior of these devices at high currents allows us to observe the effect of nonlinear elements on the stability of a feedback loop. It is quite common to encounter such nonlinear devices in practice.

At higher current levels, the steel in the transformer core begins to saturate, and thus the incremental inductance of the device drops at higher bias currents. We will ask you to measure this effect at a bias current of 0.5 A and at a bias current of 0 A.

As a start, use the multimeter to measure the coil resistance of your inductor. Also measure the resistance of the 25W power resistor you used in the previous section. These resistances become part of a model for the coil shown in Fig. 3. To complete the model, we need to measure the coil inductance. This can be done by measuring the step response from V_1 to V_2. The time constant of this response, in combination with the resistances measured earlier yields an estimate of the coil inductance L. Measure the step response for a 0.1 A step on top of a 0 A bias and on top of a 0.5 A bias. Use the DC offset control on the signal generator to set the bias current level to the desired value. What estimate of L do you get at the two bias levels?

Another way to model the system is to measure the transfer function from V_1 to V_2 as a function of frequency. Please measure this transfer function at about 30 points between 10 Hz and 1 MHz, at both 0 A and 0.5 A bias currents. You can greatly ease this measurement by using the automated measurements on the scope. Just be careful that the scope has a clean enough waveform that the data is meaningful! (It is also quite helpful here to connect the TTL out of the signal generator to the external trigger input on the back of the scope and set the scope to external trigger. Also, you can use averaging mode to reduce the measurement noise in order to get a more solid measurement.) Does this transfer function look like what you would predict on the basis of the simple model developed above? What discrepancies do you note? Try to explain these.

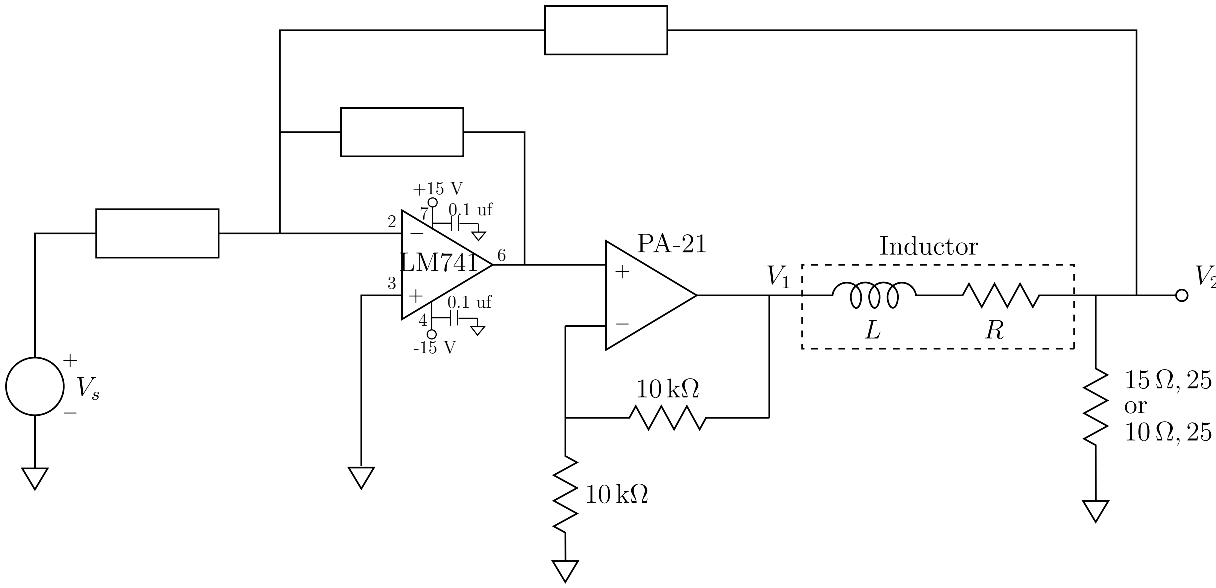

Figure 4: Closed-loop current controlled amplifier.

3. **Current controlled amplifier:** In this section, we combine the power op amp with a 741 amplifier to yield an amplifier which controls the voltage on the 25 W power resistor, and thus the current through the load inductance (to the extent that the resistor is ideal). The topology of the circuit is shown in Fig. 4. Here the 741 is to be built on the protoboard and powered from the protoboard supply. The supply connections are shown on the circuit diagram. Be sure to include bypass capacitors on each supply pin in close proximity to the chip.

   Use the model of the inductor that you developed in the previous section at 0 A bias to choose components of the control amplifier to fill in the boxes in Fig. 4. Specifically for your measured inductance, design the control amplifier to stabilize the loop with a 1000 rad/sec crossover frequency and at least 60 degrees of phase margin. Design your amplifier so that 10 volts input yields 0.7 amps coil current at low frequencies. The controller must also include an integral term so as to have high accuracy at low frequencies. Include in your report a block diagram showing the transfer functions of the key dynamic elements in the loop. For your design, sketch a root-locus plot showing how the closed-loop poles move as the control amplifier gain is varied. Also, sketch Bode plots of the negative of the loop transmission, and indicate on these the loop crossover frequency, phase margin, and gain margin. Although you are welcome to use Matlab for these calculations, please first sketch the plots by hand. (**Hint:** With respect to the practical world, in order to prevent high-frequency oscillations, be sure that the control amplifier gain falls off at least as $1/\omega$ at high frequencies, i.e. for frequencies well above crossover. Whenever you power up a new circuit, always use a scope to check for the presence of such oscillations, and be sure to eliminate them before proceding with the measurements in this lab. An oscillating amplifier will yield "flaky" results at best, and may smoke itself and/or your load at worst.)

   Choose your design values for the 0 A bias condition. Then, in the lab, verify the performance at 0 A bias. Predict and measure the closed-loop step and frequency responses.

Then also use the model you developed earlier to predict the step and frequency responses at 0.5 A bias. Then measure these in the lab. How does saturation of the magnetics affect the stability of your feedback loop?

In making the measurements above, it is important that the system is again behaving in a "small-signal" fashion. Specifically, make sure that the steps are small enough that neither of the amplifiers is hitting the supply rails. What happens when the amplifiers are allowed to saturate?

For all of the above measurements, store "interesting" data on floppy, print out, and include in your report.