MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Electrical Engineering and Computer Science

6.302 Feedback Systems

Fall Term 2002 — Issued : November 4, 2002
Lab 2 — Due : Thursday, November 21, 2002

Introduction

The purpose of this laboratory is to give you some experience compensating a system with well-known dynamics. In the prelab exercises, you analytically determined three appropriate series compensation strategies: reduced gain compensation, lag compensation, and lead compensation. In the lab you will verify that they work as predicted. The process is similar to that seen in lecture, and the material is also covered in Roberge's Operational Amplifiers pages 177–191. We have changed the numbers and are using an inverting rather than a non-inverting topology, but the ideas are the same.

Equipment

At the equipment desk, be sure to pick up the following: Lab 2 component kit, EZ hook leads, a decade capacitor, and some hookup wire. You will also need to pick up the parts that you calculated in the prelab for the various compensation schemes.

The Pseudo Op-Amp

Your experimental system will be the following "pseudo" op-amp, which gives well-known and quite repeatable op-amp like characteristics. The circuit illustrating the pseudo op-amp is shown in Figure 1.

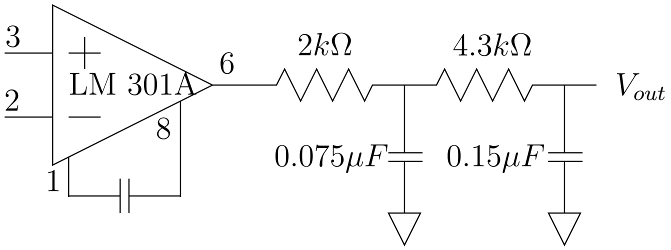

Figure 1: The Pseudo Op-Amp

Your first step is to build the pseudo op-amp circuit, being sure to use an LM301A (not a 741) for the op-amp. The 301A has the same pinout as the 741 (see the drawings posted on the walls in the lab); do not forget to power the op-amp with $+15V$ to pin 7 and $-15V$ to pin 4. For the RC network on the output of the 301A, use the precision components (1% resistors and 5% capacitors) included in the component kit. Use the decade capacitor connected by short leads for the capacitor denoted by C; you will adjust the value during the standardization portion of the lab. Use disc capacitors ($0.01\mu F$) to decouple the $\pm 15V$ power supplies–place them **on the board** between (1) $+15V$ and ground, and (2) $-15V$ and ground. We will symbolize the pseudo op-amp as in Figure 2.

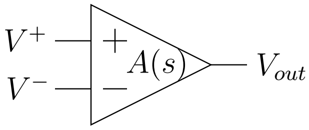

Figure 2: Pseudo Op-Amp Symbol

Throughout the course of this lab, you will be asked to use the pseudo op-amp in a number of circuits. It is imperative that you use ONE pseudo op-amp circuit for all experiments. That is, if asked to compensate the pseudo op-amp in two ways, DO NOT build two completely separate pseudo op-amp circuits. Also be careful not to burn out the "real" op-amp in the circuit. The 301A reacts very poorly (usually by dying) if pins 1, 5, or 8 are shorted to almost any potential, including ground.

If you destroy an amplifier after you have standardized it, you will have to start the lab over again.

Standardization

In all parts of the lab, the pseudo op-amp will be used to form an inverting amplifier as shown in Figure 3.

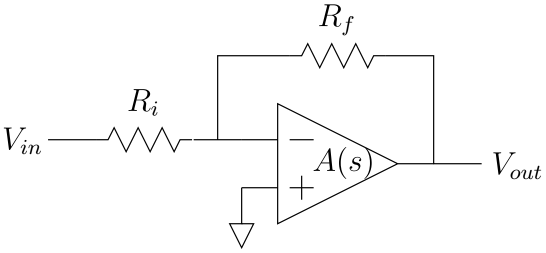

Figure 3: Basic Inverting Amplifier using Pseudo Op-Amp

If we assume that the 301A has a transfer function which is dominated by a single low frequency pole at $s = -\frac{1}{\tau}$, where $\tau >> 10^{-3}$ sec, the open loop transfer will be of the following form:

$$A(s)f(s) = \frac{a_0 f_0}{(\tau s + 1)(10^{-3}s + 1)(10^{-4} + 1)} \qquad \text{where} \quad f_0 = \frac{R_i}{R_i + R_f} \tag{4}$$

The remaining two poles at 10^3 and 10^4 rps are associated with the RC network, including the output impedance of the 301A. Not surprisingly, we see that the open-loop transfer function depends upon two of the "real" op-amp characteristics – its DC gain a_0 and the location of the low frequency pole ($-\frac{1}{\tau}$). Hence, the open-loop transfer function will in general vary somewhat depending on the characteristics of the particular circuit which you will build.

In order to obtain experimental results which agree with your analytic prelab calculations, it will be necessary to *standardize* the op-amp circuit which you have built. Since we will be concerned with the issues of compensation and the degree of stability in the lab, standardization will consist of making the behavior of the pseudo op-amp in the vicinity of the anticipated crossover frequency a known function.

Of the two parameters a_0 and τ, we have no control over a_0, but we have complete control over the value of τ by changing the compensation capacitor C (the capacitor between pins 1 and 8 of the 301A) using the decade capacitor. The following procedure can be used to standardize your pseudo op-amp circuit:

1. Build the inverting amplifier circuit of Figure 3, setting $R_i = 62k\Omega$ and $R_f = 220k\Omega$ using 1% resistors.

2. The driving source impedance in this lab must be low. A resistive divider attenuating the signal generator output and located close to the pseudo op-amp is suggested. A suggested attenuator is shown in Figure 4. Note that the output of the attenuator (To circuit) provides the input to your amplifier setup (V_{in}).

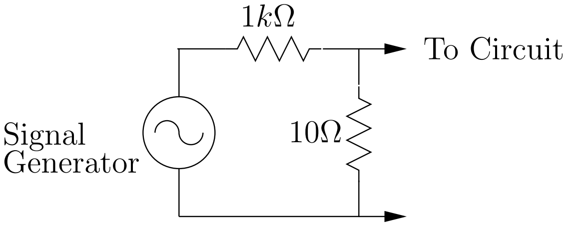

Figure 4: Attenuation Circuit

3. Apply a low frequency, small amplitude square wave to the attenuator. The assumptions required for linear analysis are severely compromised if the peak to peak magnitude of V_{in} (the output of the attenuator) exceeds $\sim 50mV$. (In most cases, inaccurate lab results are traceable to this sort of error.)

4. Adjust the value of the compensating capacitor C (the decade capacitor) so that the circuit is on the verge of instability. The longer the step response "rings" before dying out, the closer the poles are to the $j\omega$ axis. The record for ring time is about 10 sec, but 0.2 to 0.5 sec is sufficient. A ballpark value for C is on the order of 5000 pF. Be sure that the circuit is *ringing* and not *oscillating.* Note that this procedure is the experimental equivalent to process of determining τ analytically in the prelab to achieve a system with zero phase margin.

DO NOT CHANGE THE COMPENSATION CAPACITOR C FOR THE REMAINDER OF THE LAB

Initial Measurements

Now connect your standardized pseudo op-amp circuit as an inverting gain of ten amplifier by replacing the $62k\Omega$ resistor with a $22k\Omega$ resistor. Again, you should use a 1% precision resistor. This circuit will comprise your basic uncompensated system, with properties calculated in the prelab. This is illustrated in Figure 5.

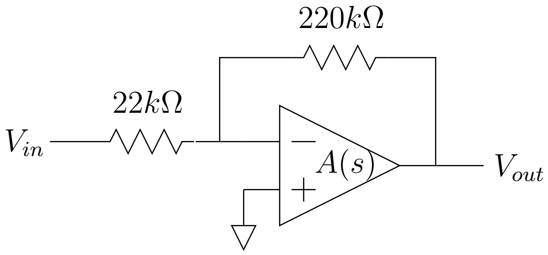

Figure 5: Uncompensated System (Gain of 10 Inverting Amplifier)

Measure the time and frequency domain responses of your amplifier (damped natural frequency ω_d, peak time t_p, and percent overshoot $P.O.$; peak magnitude M_p, and peak frequency ω_p.) Deduce the equivalent damping ratio and natural frequency, and compare these values with your predictions from the prelab.

Compensation

Your are now ready to compensate the system to improve its phase margin by:

1. Reducing the DC open-loop gain
2. Lag compensation
3. Lead compensation

You may not change the value of the compensating capacitor C or elements in the RC network of the pseudo op-amp, or load the network unreasonably to implement your compensation. The circuits for each compensated system are shown in the prelab. You should use the component values calculated in the prelab for R' (reduced gain), R_{lag} and C_{lag} (lag compensator), and R' and C_{lead} (lead compensator).

Take time domain and frequency domain measurements for each compensated system, and deduce the damping ratio, natural frequency, and phase margin. You should measure the bandwidth for each system as well. Convince yourself that the step and frequency responses that you measure are in reasonable agreement with your prelab designs.

Writeup

You should include the following:

1. Your prelab, including block diagrams, Bode plots, root loci, closed-loop pole/zero locations, and predicted responses for the uncompensated and compensated systems.
2. The component values you used to implement each compensator.
3. Measured responses and calculated closed-loop parameters (ζ, ω_n, and ω_b) for each compensator.
4. A discussion of the advantages and drawbacks of each compensator (such as DC gain, bandwidth, transient behavor, etc.)