MECH 421: Mechatronics System Instrumentation
2020/21 Winter Session – Term 2

Lab 1 – Power Voltage Amplifier

Pre-lab due: Feb 8, 2021
Lab report due: Feb 22, 2021

1 Objectives

- Design a voltage amplifier using a power operational amplifier.
- Measure DC motor impedance frequency response.
- Measure the voltage amplifier step response.

2 Lab Description

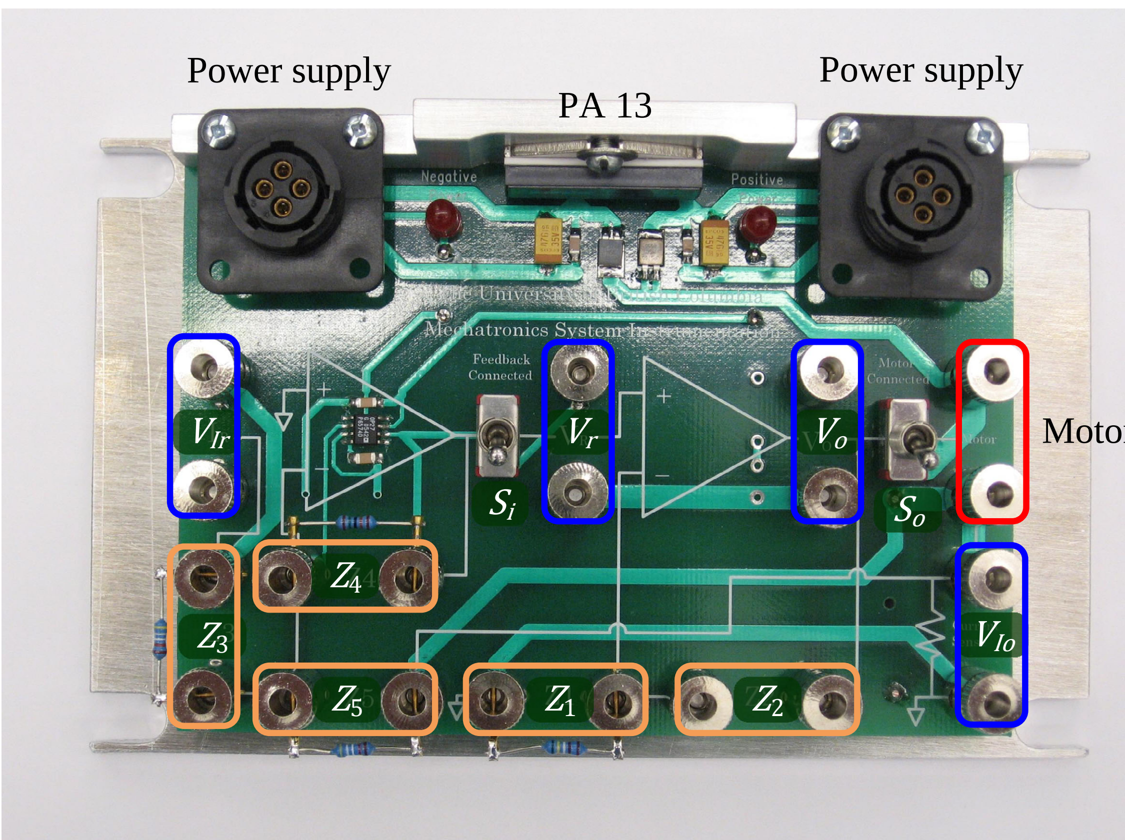

Figure 1: Picture of the power amplifier board.

Figure 1 shows a picture of the power amplifier board that we will use during Lab 1 and Lab 2. A simplified circuit schematic is shown in Figure 2. The system consists of two parts: a voltage stage based on a power op-amp (PA13 from Apex Microtechnology) and an analog current controller based on a signal op-amp (OP27 from Analog Devices). The power op-amp is attached to an aluminum heat sink and the signal op-amp is mounted on the printed circuit board. If you are interested in learning more about this device, please refer to the data sheet in this link[1].

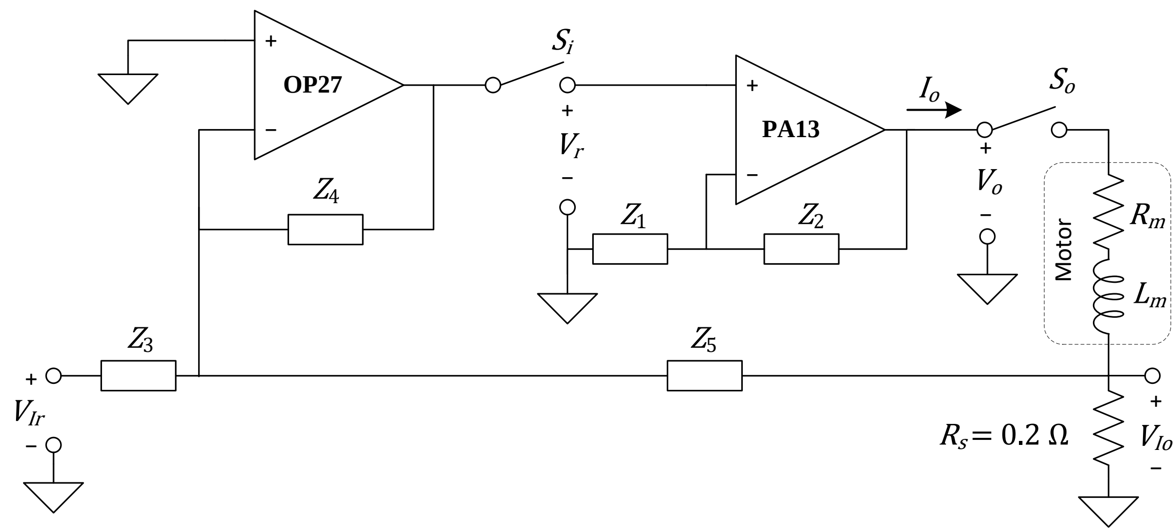

Figure 2: Power amplifier simplified schematic diagram.

In this lab, we will perform experiments on the voltage stage only. We will connect two resistors Z_1 and Z_2 to set the gain and bandwidth of the voltage stage. Use the two pairs of sockets labeled as Z_1 and Z_2 in Figure 1 to connect the two resistors Z_1 and Z_2.

There are two switches S_i and S_o at the input and output of the power op-amp. The input switch S_i connects/disconnects the current controller. In this lab, we will disconnect the current controller by setting S_i to the position shown in Figure 1. This allows us to connect a signal generator for an external reference voltage V_r. The output switch S_o connects/disconnects the brushed DC motor load (shown disconnected in Figure 1). In this lab, we will disconnect the motor in Section 4.1 and connect the motor in Section 4.2. Use the pair of sockets labeled as `Motor` in Figure 1 to connect the brushed DC motor. There is a shunt resistor $R_s = 0.2\,\Omega$ to measure the current through the motor winding.

The board provides dedicated sockets for three voltage measurements: V_r, V_o , and V_{Io}. Please do not use any other sockets for measurements. Here, V_r is the voltage stage input voltage, V_o is the voltage stage output voltage, and V_{Io} is the current-sensing voltage. When the output switch S_o is on, the relation between the current-sensing voltage V_{Io} and the output current I_o is

$$I_o = \frac{1}{R_s} V_{Io}.$$

[1] `https://www.apexanalog.com/resources/products/pa13u.pdf`

3 Pre-lab Assignment

1. Select the values of Z_1 and Z_2 such that the DC gain of the voltage stage is 11.

2. Based on the PA13 open-loop frequency response shown in Figure 3, calculate the closed-loop bandwidth of the designed voltage stage. Also, draw the Bode plot and expected step response of the closed-loop transfer function $V_o(s)/V_r(s)$.

3. Assuming the motor winding resistance is $R_m = 3\,\Omega$ and the motor winding inductance is $L_m = 1\,\text{mH}$, calculate the transfer function from the output voltage V_o to the output current I_o and the time constant. Also, draw the Bode plot of $I_o(s)/V_o(s)$.

4. Draw the Bode plot of $V_{Io}/V_r(s)$ and its step response.

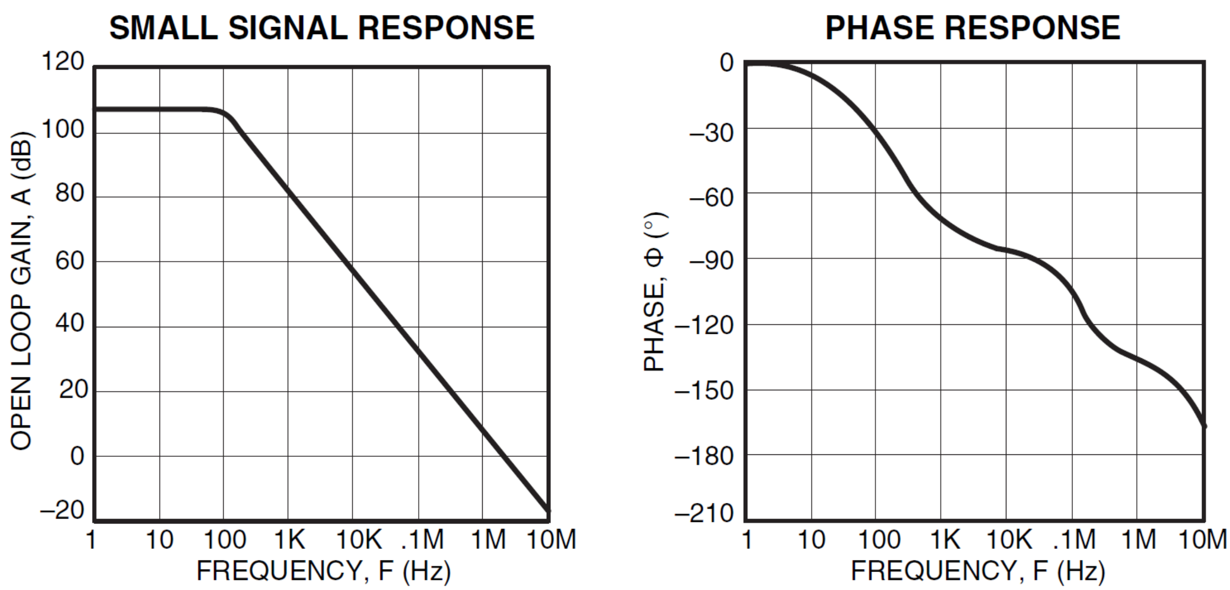

Figure 3: Open-loop frequency response of PA13.

4 Lab Assignment

In this lab, please make sure to turn off the input switch S_i by setting it to the position shown in Figure 1. This will disconnect the current controller from the voltage stage. The signal generator output should be connected to V_r. There are three pairs of sockets for voltage measurements V_r, V_o, and V_{Io}. Please make sure that the banana connector ground terminal is oriented towards the bottom side of the board as shown in Figure 1.

4.1 Voltage stage without motor load

In this part, turn off the output switch S_o by setting it to the position shown in Figure 1. This will disconnect the motor from the voltage stage.

4.1.1 Step response

In this experiment, you will apply a step reference voltage V_r using a signal generator and measure the output response V_o using an oscilloscope. You should also measure V_r using an oscilloscope to check if the measured amplitude matches with the signal generator indicator. (You may observe a difference. This is because the output amplitude of the signal generator is affected by the load impedance).

Set the signal generator to output a square wave at 10 Hz. Measure the voltage stage output signal V_o for each of following amplitudes of reference signal V_r: $0.2\,\mathrm{V_{pk\text{-}pk}}$, $0.5\,\mathrm{V_{pk\text{-}pk}}$, $2.0\,\mathrm{V_{pk\text{-}pk}}$, and $5.0\,\mathrm{V_{pk\text{-}pk}}$

Draw the four step responses on your lab reports. For each of them, calculate the rise time (from 10 % to 90 %) and the percentage over shoot.

Draw **normalized** step responses of the above four results on a single graph, compare their difference, and explain why. Here, *normalized* means with respect to the steady-state value of the step response (i.e., scale them such that all steady-state values are unity).

4.1.2 Frequency response

Set the signal generator to output a sine wave with an amplitude of $0.2\,\mathrm{V_{pk\text{-}pk}}$. Measure the frequency response from 50 Hz to 10 MHz at 20 frequency points, which should be nearly equally spaced in **log scale**. Record the amplitude of V_r and V_o and their phase shifts. Calculate the $-3\,\mathrm{dB}$ bandwidth of the closed-loop system and compare with your pre-lab prediction. If the output waveform has significant distortion (i.e., not sinusoidal or peaks clipped off), you should reduce the signal generator amplitude to ensure that the output from the power amplifier V_o remains sinusoidal.

4.2 Voltage stage with motor load

In this part, turn on the output switch S_o to connect the motor.

4.2.1 Step response

Set the signal generator to output a square wave at 10 Hz. Measure the power amplifier output current V_{Io} for the input signal $V_r = 0.2\,\mathrm{V}_{\text{pk-pk}}$. Calculate the time constant and compare with your pre-lab.

4.2.2 Frequency response

Measure the frequency response from 50 Hz to 50 kHz at 20 frequency points, which should be nearly equally spaced in **log scale**. Take more data points around the break frequencies to clearly see the response. At each frequency point, record the amplitude of V_r, V_o, and V_{Io}, and their phase shifts relative to V_r.

Note: in order to measure the frequency response correctly, you should set the excitation input amplitude very carefully. At low frequencies, too large an input amplitude of V_r will result in excessive current into the motor. You should monitor the output current level, and make sure that V_{Io} is less than $0.1\,\mathrm{V}_{\text{pk-pk}}$ (i.e., I_o is less than $0.5\,\mathrm{A}_{\text{pk-pk}}$) for all times. At high frequencies, too large an input amplitude of V_r will result in amplifier slew rate saturation. If the input amplitude of V_r is too small, on the other hand, the output current sensing voltage V_{Io} will be immersed in noise and thus cannot be measured accurately. In your experiment, you should gradually increase the input voltage V_r while monitoring the output voltage V_o and current sensing voltage V_{Io} in order to make sure that 1) there is no slew rate saturation on V_o and 2) V_{Io} is below $0.1\,\mathrm{V}_{\text{pk-pk}}$. Under these constraints, set V_r as large as possible.

Based on these measurements, calculate the output current $I_o = (5\,\Omega^{-1})V_{Io}$ at each frequency point.

1. Draw the Bode plot of $V_o(s)/V_r(s)$
2. Draw the Bode plot of $I_o(s)/V_o(s)$
3. Draw the Bode plot of $V_{Io}(s)/V_r(s)$
4. From these measurement results, identify the motor resistance and inductance values.

4.3 Destabilize the voltage stage

In this part, turn off the output switch S_o to **disconnect** the motor and turn off the input switch S_i to **disconnect** the current controller (positions as shown in Figure 1.

Add a 470 nF capacitor in parallel with Z_1. Observe the PA13 output V_o when the signal generator is turned off. Explain the behaviour of the output V_o.