MAE 106 Laboratory Exercise #1
Laboratory Tools and Control of a Motor

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Introduction

There are two parts to this lab exercise. In the first part, you will learn how to use the oscilloscope, function generator, breadboard, ohmmeter and potentiometer. In the second part, you will learn how to use a low power signal and a power transistor to control the speed of a motor. There are 4 practical exams problems for which you will have to demonstrate something to the TA. There is also a brief write-up (read the last page now to see what it is!!).

Note: When making electrical circuits in lab, a mistake in your wiring may result in a component getting "fried." If you smell something burning, immediately turn off your proto-board and "debug" your circuit.

PART 1: Laboratory Tools

The oscilloscope and function generator are useful tools for making measurements and debugging machines. The solderless breadboard is useful for building circuits. Potentiometers are a very common circuit element for controlling a voltage or sensing a rotation.

REQUIRED PARTS:

Qty	Parts	Equipment
1	50K Potentiometer	Trainer Kit (XK-550)
1	150Ω Resistor	Oscilloscope with scope probe
Var.	22 gauge wire	

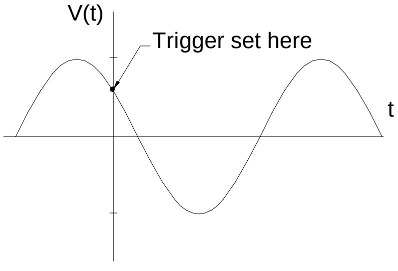


Figure 1 – Trigger and Sweep Rate

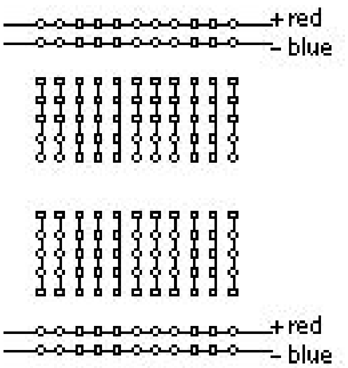


Figure 2 – Solderless Breadboard

1 The Oscilloscope and Function Generator

The oscilloscope is used to measure and view voltage as a function of time. A voltage waveform such as $v(t) = a \sin\omega t$ will appear on the scope's cathode ray tube much like you would plot it on a piece of paper. The voltage at which the trace begins is adjusted with the *trigger level*. The duration of the waveform that appears on the screen is determined by the *sweep rate* (or time scale) of the scope. You can refer to the HP oscilloscope user's guide to better understand its basic operation.

A *function generator* is a device that produces voltage waveforms such as sine, square, and triangle waves, all with variable *amplitude, frequency,* and *offset.* A function generator is often used to provide an input signal to the oscilloscope. For example, the function generator can produce a voltage with the form

$$v(t) = v_{0ffset} + a \sin\omega t$$

where the amplitude a, the frequency ω, and the offset v_{0ffset} are all adjustable.

Connect the oscilloscope channel 1 input scope probe to the trainer kit function generator output (Freq.), with the scope alligator clip to GND (Note: A BNC connector is a common type of connector with a bayonet coupling mechanism. BNC stands for (Bayonet Neill Concelman), because the connector was invented by and named after Amphenol Engineer Carl Concelman and Bell Labs Engineer Paul Neill. It was developed in the late 1940's.

Set the function generator to output a sine wave at about 100 Hz. Press the **Auto-scale** button on the scope. When you push the button, the scope measures the maximum and minimum values of the current signal, and sets the screen scaling to match these values. Get the scope to display the peak-to-peak voltage of the sine wave by pressing **Voltage** and then **Vp-p** (make sure the **Source** option for the **Voltage** function measurement is set at **Line 1** – this will use channel 1 as the input line). Now adjust the function generator to output a 2 Vpp (volts peak-to-peak) sine wave at 100 Hz with no offset (**DC offset** button out). On the scope, make sure the **Probe** setting is 1 (so voltage is multiplied by 1; as explained, some probes divide the voltage by 10, and if you are using those probes rather than BNC cables, the Probe setting should be 10X). Make sure the **coupling** is set to DC (under channel **1)**.

P1. Plot the trace on the scope. (You should see the sine wave clearly now). Label plot with the voltage and time scales.

Q1. Using the utilities on the scope, obtain and record Vmax, Vmin, Vp-p, Vavg, Period, frequency, and Duty Cycle (under **Voltage** and **Time**). Notice that these functions won't work unless at least one period of the whole voltage signal appears on the screen.

Q2. Turn the **Volts/Div**, **Time/Div**, and **position** dials on the scope. Does the **Volts/Div** dial change the amplitude of the sine wave? Does the **Time/Div** dial change the frequency of the sine wave? Does the **position** dial add a constant voltage to the signal? What do these dials do?

P2. Adjust the sine wave amplitude to 1Vpp at 200 Hz. Plot (on the same plot as for P1) the trace on scope using the same voltage/time scales as before.

Q3. Make the grid turn off and on (under **Display**). Change trigger (under **Source**) from 1 to 2. What happened to the sine wave? Change it back to 1. Why does it do this? Hint: think about what the scope must do to make a sine wave appear without moving (rolling) across the screen.

Q4. Offset the sine wave by pushing the **DC offset** button on the function generator and adjusting the dial. What does the trace do? On the scope, set the coupling to AC (under channel **1**). Now what does the trace do when adjusting the DC offset? What is the purpose of using AC coupling?

P3. Remove the DC offset (**DC offset** button out) and get the function generator to output square and then triangle waves. Plot the traces in **one** plot.

Practical Exam 1: Ask the TA to come by your station and set the voltage and frequency of a sine wave on the frequency generator. Demonstrate to the TA that you can measure the amplitude and frequency of the sine wave. If the TA is busy with another group, you can go ahead with the lab and ask the TA to come by later.

2 Solderless (Breadboards)

The electronic breadboard (solderless breadboard) is used to wire up temporary circuits. Electronic components and wires (use solid wires at 22-gauge thickness) are inserted into the numerous sockets (holes) on the board. The sockets (dots) are connected internally (lines) as shown in Figure 2. A good method for wiring complicated circuits is to connect the source voltage (+5V, ±15 V) and ground terminals from the trainer kit to the long narrow horizontal strips (Figure 2). Electronic chips now have ready access to power through short wires to sockets along the long strips.

After wiring your circuit to the solderless board, you may use the oscilloscope to measure voltages at various points on the circuit using the scope probe. Note that the scope probes will usually divide the voltage they read by 10, so you must compensate for this by setting **Probe** (under channel **1**, or appropriate channel number) on the scope to 10 (this will multiply the voltage value by 10).

3 Potentiometer and Voltage Divider Circuits

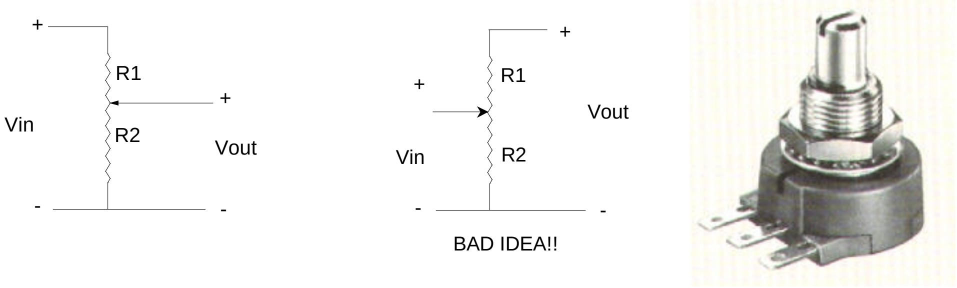


Figure 3A & 3B – Potentiometer circuits, and actual potentiometer. In the circuit diagrams, the wiper is the wire with an arrow on it. For the actual pot, unless otherwise labeled, the wiper is usually the middle connector (how could you check this with an ohmmeter?).

A potentiometer (also called *pot*) is a device that can provide a variable resistance between 2 of its leads. As you turn the knob of a pot, the wiper moves along a resistive element. Look at a broken pot in lab and see if you can figure out how it works. Figure 3A shows a pot being used to produce a variable output voltage.

Q5. Derive V_{out} as a function of V_{in} ,R_1, and R_2 for Figure 3A.

Q6. Explain why you should never use the circuit in Figure 3B.

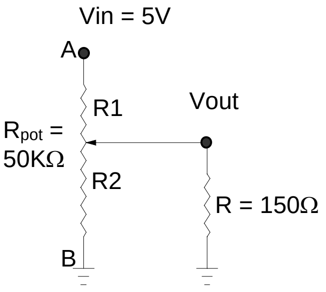
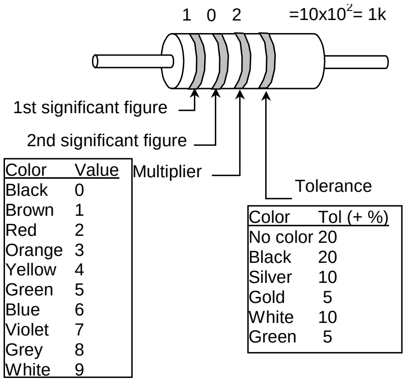


Figure 4. Circuit for question 9



Color	Value
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Grey	8
White	9

Color	Tol (+ %)
No color	20
Black	20
Silver	10
Gold	5
White	10
Green	5

Figure 5. Resistor Color Code

Using the color code at the bottom of the page, pick out a 150 ohm resistor. Confirm the resistor value by measuring it with an ohmmeter. Then wire the circuit shown in Figure 4 on the breadboard. With R = ∞ (i.e. an open circuit), measure V_{out} in five approximately equally spaced potentiometer positions (i.e. full clockwise, full counter-clockwise, the center, etc.). Repeat the test with R = 150Ω.

P4. Sketch V_{out} vs. pot angle for both cases.

Q7. One plot is linear and one is not. Using your knowledge of circuit theory, show mathematically that this is the case by deriving the equation for V_{out} as a function of θ (don't plug actual values in until you derive the equation!). Note: first derive the equations that relate R1 and R2 to pot angle ($0 \leq \theta \leq \theta_{max}$). Assume that R1 varies linearly with θ. Under what conditions would a pot be a good way of making an adjustable voltage source? Brainstorm two possible uses for potentiometers on your final project.

Practical Exam 2: Show the TA that you can calculate the value of a resistor using the color code, and that you can measure it using the Ohmmeter. Explain to the TA why you will never wire a potentiometer as shown in Figure 3B. Explain to the TA how you might use a potentiometer for you final project.

PART 2: Control of an Electric Motor

REQUIRED PARTS:

Qty	Parts	Equipment
1	N-type Power MOSFET (IRF510 or NTE2382)	Trainer Kit (XK-550)
1	LM324 Quad Op-amp chip	Oscilloscope with scope probe
1	50kΩ potentiometer	Small DC motor
1	470Ω resistor	Integrated circuit puller
1	1kΩ resistor	Grounding wrist strap
1	47K Resistor	
1	100Ω resistor, 2 Watt (with smaller ga. wire leads)	
var	22 gauge (AWG) wire	

1 Introduction

Engineers use electric motors for a variety of applications requiring mechanical movement (robots, automation equipment, disk drives, etc.). A motor is only useful, however, if we know how to control it. Sometimes we want to control the motor's position (computer disk drives, CD players, plotters), sometimes its speed (cruise control on autos, CD players), and sometimes its torque (robots, some heavy machinery). In this lab, we will investigate controlling the voltage across a motor, which, assuming there are not external forces acting on the motor, will control the speed of the motor. In other words, if the motor load is just inertial, then the steady-state speed of the motor is proportional to the voltage across its terminals.

In this part of the lab, we will investigate two circuits that can control the voltage across a small electric motor. Each circuit will involve the use of a MOSFET and/or an operational amplifier (or op-amp). The op amp circuit will utilize "feedback" to control the motor voltage. So, in this experiment you will gain insight into how DC brushed motors behave, how to control the power supplied to a motor with a MOSFET, and how to regulate the behavior of the motor with an op-amp controller.

2 Voltage Follower for Voltage Control

Op amps are often used in analog circuits. They take 2 input voltages at their inputs (the inverting input (V_-) and the non-inverting input (V_+)) and produce an output voltage

$$Vout = K(V_+ - V_-), \qquad \text{where } K \approx 1\text{x}10^5. \qquad (3)$$

They also have a very high input resistance, so for practical purposes they draw no current at their inputs. These characteristics of op amps allow them to serve many circuit functions, such as voltage addition and subtraction, feedback control, and buffering. The op amps used in this lab can output only tens of mA of current; you will calculate the exact value in the lab.

In Figure 2, an op amp is used in a voltage follower circuit. In this circuit, the op-amp attempts to adjust the output voltage (Vout) so that it "follows" (makes it equal to) Vin. This circuit is also called a buffer or isolation amplifier because the output current does not affect the input voltage (Vin). The load resistance (R_L) draws current from the op-amp. A small value of R_L is considered a “large load.” A large value of R_L is a “small load.” Note that large loads can cause a drop in voltage in a voltage source if the voltage source cannot supply sufficient current.

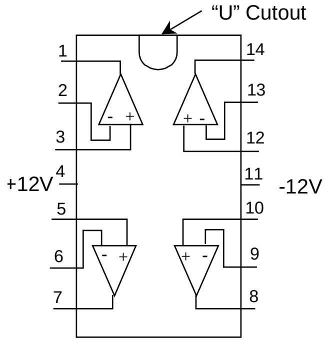


Figure 1 – LM324 Quad Op-Amp Chip

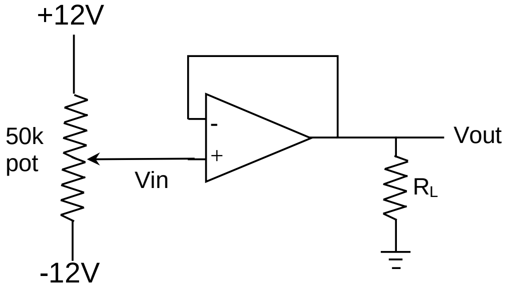


Figure 2 – Voltage Follower Circuit.

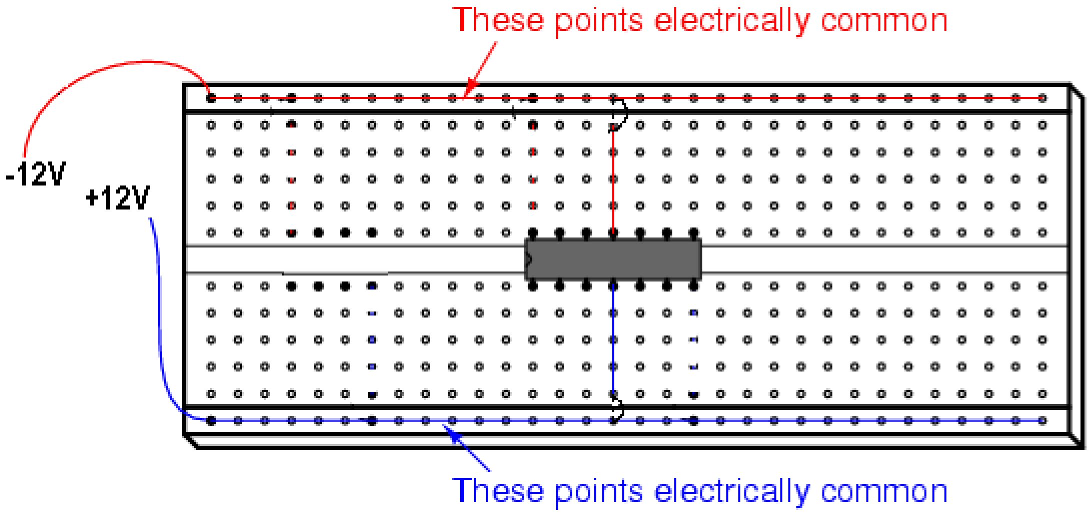


Figure 3 – Suggested Layout of Circuit on Solderless Breadboard

Construct the circuit shown in Figure 2 (suggested layout is in Figure 3). We will use the LM324 chip (Figure 1), which has 4 op-amps built on the chip. Power must be supplied at pin 4 (positive voltage) and pin 11 (negative voltage), else the chip will burn out.

Q1 Using the op-amp equation above, derive the equation of Vout for the buffer circuit.

Q2 There are limitations in the buffer circuit in Figure 2. That is, there are conditions when the op-amp would not be able to make Vout = Vin. Discuss 2 limitations.

P1 Measure Vout and Vin across the full range of pot angle positions, for several values of the pot angle. Do this with R_L = 1 kΩ and with R_L = 470Ω. Sketch Vout vs. Vin for both R_L values on one plot.

Q3 Which plot follows Vin more closely, particularly at the voltage extremes of Vin? Explain. Using your results, calculate the maximum current that your op amp can supply. Is the 470Ω resistor close to blowing up (consider its power rating)?

Suppose you replace R_L with a motor whose resistance is 30Ω, and you hold the shaft of the motor still. Would you be able to control the amount of torque that the motor can generate? Note: When to motor shaft is held still, the amount of torque that a DC motor generates is proportional to the current going through it.

Q4 THOUGHT EXPERIMENT: If you changed the power input to the LM324 chip to +5V (pin 4) and 0V (pin 11), and adjusted Vin over the +12V to –12V range, do you think Vout would follow Vin? Explain. NOTE: DO NOT ATTEMPT THIS; IT CAN BLOW THE OP AMP AND POT!

3 Open-Loop MOSFET Voltage Control Circuit

A MOSFET is a type of transistor that restricts or allows current flow through the *source* and *drain* leads based on voltage applied at its *gate* with respect to the source (V_{GS}). It can be thought of as a variable resistor whose resistance value is determined by V_{GS}. For the MOSFET's used in class, the effective resistance between source and drain (R_{DS}) varies between infinity (with V_{GS} < 3 or 4 volts) and about ½ ohms (with V_{GS} ~5-6 V). These characteristics allow MOSFETS (and other transistors) to be used as either current amplifying devices (power MOSFETS for motors, etc.) or switches (low power MOSFETS in computers).

Construct the circuit shown in Figure 4 (make load resistance $R_L = 100\Omega$ at 2 Watt rating). In this circuit, we directly control the MOSFET gate voltage (V_G) by turning the potentiometer (recall that V_{GS} will vary linearly with the pot angle), which ultimately controls the motor voltage (V_{motor}). In this section, we will study how V_{motor} varies as we vary V_{GS}.

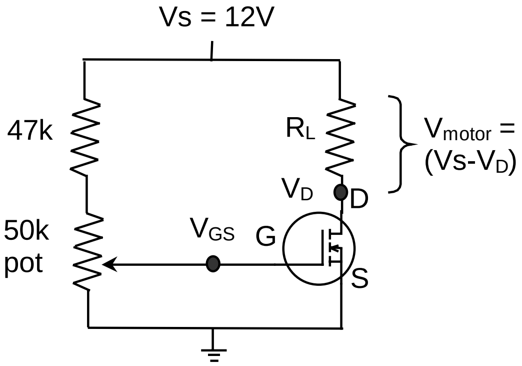


Figure 4 – MOSFET voltage control circuit

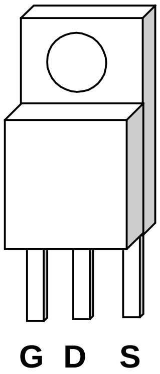


Figure 5 – MOSFET leads

Q5 Derive the following formula relating the MOSFET resistance (R_{DS}) to Vs, V_D, and R_L.

$$R_{DS} = V_D R_L/(Vs – V_D)$$

Q6 Consider the circuit in Figure 4 and assume that R_L is a motor. Explain how turning the pot (which we control) ultimately controls motor voltage (V_{motor}). Include in your explanation the role of the pot and the MOSFET.

P2 Measure V_{GS}, and V_D at enough potentiometer positions to produce a nice plot of R_{DS} vs. V_{GS} and V_{motor} vs. V_{GS} (on same plot, not V_D vs. V_{GS}). Take more measurements in the area of pot positions where V_D changes quickly. Use the equation above to compute R_{DS}. Plot V_{motor} with respect to V_{GS} (i.e. the input voltage). Is this relationship linear?

Q7 Replace the load resistor (R_L) with a small DC motor. Slowly increase V_{GS} from a value of zero and visually observe the resulting changes in motor speed. Try to make the motor shaft rotate at approximately once per second. Is it difficult? Does the speed of the motor relate linearly to the V_{GS}? Explain why this is so. Would you say that you are controlling motor voltage well?

Q8 Measure the DC resistance of the motor with an ohmmeter and report the value. You have just measured R for the equation 1. Disconnect your motor from the circuit and connect it to an oscilloscope. What is the maximum voltage you can generate by hand? Describe how B_1 (in equation 1) can be measured experimentally. Be precise in describing the experiment you would perform.

Practical Exam 3: Demonstrate to the TA that you can control the speed of your motor with the potentiometer.

4 Closed-Loop Voltage Control Circuit

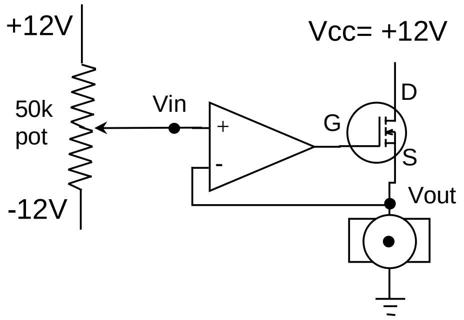


Figure 6 – Closed-Loop Voltage Control Circuit. ***(Note: Power connections to Op Amp not shown!)***

In Part 2, we learned that an op-amp might not provide sufficient current to run a motor. MOSFET's may be necessary to control higher levels of current required by devices such as heaters and electric motors, but they are highly non-linear to the input voltage. Now we will add "feedback" to our controller. A controller that uses feedback takes information about some state in our system (voltage, position, velocity, temperature, etc.) that is measured by a sensor (voltmeter, pot, tachometer, thermocouple, etc.), and uses it to compute a "control" (an input to the system that we control, often denoted "u"). The control is designed to make the state of the system be what we want it to be.

Construct the circuit shown in Figure 6.

Q9 Explain how turning the pot (which we control) ultimately controls motor voltage (Vout). Include in your explanation the role of the pot, op-amp, and the MOSFET.

P3 Make about five measurements of v_{in} and v_{out} as v_{in} varies between 0 and 13 volts. For each pot setting of v_{in}, measure v_{out} (let the motor shaft spin freely). Plot v_{out} versus v_{in} on the same plot as P2.

Q10 Try again to make the motor rotate at approximately one cycle per second. Explain why it is easier than before. Explain why this is a better voltage control circuit than the previous one.

Practical Exam 4: Demonstrate to the TA that you can control the speed of your motor with the potentiometer. You should be able to control it more precisely than in Practical Exam 3 – Explain why to the TA.

Q11 In this experiment, you focused on controlling the motor voltage, which controls the motor speed when there are no disturbances on the motor shaft (e.g. when you are not holding the shaft). In the real world there are often unexpected disturbances that produce undesired changes in the motor speed (imagine an electric car that has to go up a hill, or, try stopping the motor with your hand). Suggest an improved method for controlling motor velocity (hint: consider how you might design a cruise control system a car using a tachometer).

WRITE-UP

- due at your next laboratory session
- each student must complete his or her own write-up
- make sure to use your own words!!
- include your name and laboratory time on the write-up
- the write-up must be type-written
- Graphs for the lab write-up must be generated using Excel or Matlab, and must include labels on the axes, voltage and time scales used on the scope, and a legend for multiple-line plots.
- Page limit = 2 pages, including graph

1. Briefly explain uses for an:
    a. oscilloscope
    b. function generator
    c. solderless breadboard
    d. potentiometer
2. Briefly explain how a low-power signal and a power MOSFET can be used to control the speed of a motor.
3. Briefly explain why the operational amplifier made it easier to control the speed of the motor
4. Turn in the graph for P2 and P3 from PART 2 of the laboratory exercise