

Circuits Design Project: Final

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Executive Summary:

This project uses inverting and noninverting op-amps to analyze their behavior and test an application. Op amp structure and functionality, voltage division, and iterative design concepts are the topics being covered. This assignment was designed in two parts, the first being solely on paper, and the second to be actually built. The first part is asking to maximize the power output across a 10k load resistor using $\mu A741$ op amps, whose spec sheet is linked in the assignment for students' convenience. A MATLAB script is also requested such that students learn how to test numerous resistor values efficiently. The next part is to be built and uses a power supply uses OPA552 op amps and a 3V DC motor. The assignment is to find the resistor values for each op amp such that they deliver the necessary voltage and current for optimal functioning of the DC motor. The circuit has a SPDT switch where either direction goes to one of the op amps, and then the op amps go to the motor. The idea is, if done correctly, the switch will have the capability of changing the direction of which the motor spins due to either op amp's output. Students can put a bit of masking tape onto the shaft of the motor in order to more easily determine the direction that it's spinning.

The cost is high, but an investment for an entire semester and beyond. We opted for a variable power supply to ensure consistent and precise voltage to the op amps, which makes up the largest part of total cost. The total cost is \$105.78, but the motor and op amps alone only cost \$12.35 collectively.

Introduction:

This project explores the use of inverting vs. non-inverting op amps to act as directional control for a DC motor. The applications of op-amps are numerous. For instance, they are frequently used as voltage amplifiers that can amplify, attenuate, and/or invert a signal. They can also be used to perform basic mathematical operations. For this design project, you will be exploring two of the most common op-amp circuits; the inverting and the non-inverting op-amps.

You will demonstrate your understanding of the following concepts:

- Basic structure of an operational amplifier (i.e. what the labels for each terminal actually mean)
- Assumptions for the ideal operation of an op-amp
- Signal control using inverting and non-inverting op-amps along with NVA
- Basic switching and voltage division
- Iterative design using MATLAB or equivalent software

This assignment has two parts:

Part 1: Designing to maximize power output. DO NOT BUILD. Not a good idea to test components at the maximum ratings.

You will use the specifications for a $\mu A741$ operational amplifier found [here](#) to maximize the power to a 10 [k Ω] load resistor. You will design this system considering the following given information:

- The voltage does not vary with time, so the slew rate is not of concern. You should take into account the maximum output voltage swing (saturation voltage) of the op-amp and the short-circuit output current (saturation current). These can be found in the specs.
- The circuit will use three rechargeable AA batteries (nominal 1.2 [V] each) as a source. A singular SPDT switch will then allow a user to select between an inverting and a non-inverting op-amp. Resistor values are limited to those that can be found in the Makerspace. You may not create a “custom” resistor using series/parallel combinations.

Deliverables for Part 1:

- A complete diagram of the circuit (source, switch, resistors, op-amps, load resistor)
- Nominal values of resistors used with inverting and non-inverting op-amps
- Maximum power dissipated by the 10 [k Ω] resistor for each of these cases
- Short-circuit output current and output voltage for each of these cases.

Recommended Software: MATLAB or equivalent.

Part 2: DC Motor Control. You will build this circuit to demonstrate your understanding of the physical construction of op-amp circuits. Using the specs for the DC motor found [here](#), you are to design and build a circuit that is capable of delivering the necessary voltage and current. Your circuit should resemble the circuit from part 1.

Your circuit should have:

- Batteries
- Switch(es)
- Inverting and non-inverting op-amps
- Motor and 47 [Ω] resistor (the load)

Deliverables for Part 2:

- A complete diagram of the circuit (source, switch, resistors, op-amps, motor)
- Nominal values of resistors used with inverting and non-inverting op-amps
- Nominal resistor value used for load (may be a combination of resistors in the Makerspace)
- Physical circuit matching the qualities listed above
- Measured voltage across and current through the motor for both cases

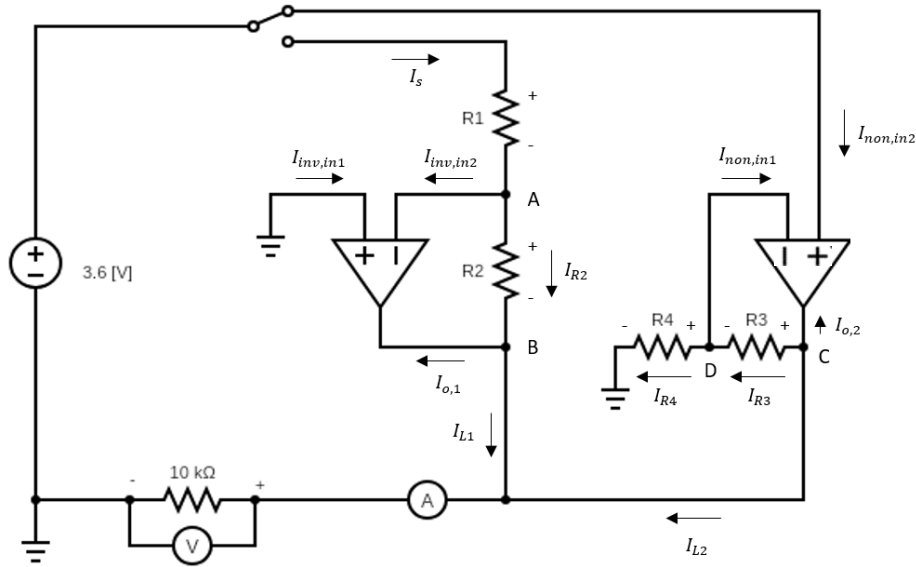
Recommended Software and Resources

- MATLAB or equivalent
- [This guide](#) gives some introductory information about wiring an inverting op-amp using a voltage source. We will power your op-amp with a voltage source, but you are responsible for constructing the rest of the circuit on your breadboards.
- You can find the specs for the op-amp you will be using [here](#). You will be using the OPA552 P Package. Two terminals require no connection. The flag terminal is used to monitor thermal shutdowns; you will not connect this as you will only be demonstrating your circuit once.

Solution:

Part 1:

The circuit for part 1 is given by the following:



We will first solve for the inverting op-amp. We shall first construct KCL at node A, noting that the voltage at A and input currents are zero according to the assumptions for an ideal op-amp:

$$I_s = I_{inv,in2} + I_{R2}$$
$$\frac{V_s - V_A}{R1} = 0 + \frac{V_A - V_o}{R2}$$
$$V_o = -\frac{R_2}{R_1} V_s$$

Now, we will construct KCL at node B:

$$I_{R2} = I_{o,1} + I_{L1}$$
$$\frac{V_A - V_o}{R2} = I_{o,1} + \frac{V_o}{R_L}$$
$$I_{o,1} = -\frac{V_o}{R_2} - \frac{V_o}{R_L}$$

We thus have expressions for the output voltage and output current of the inverting operational amplifier. Let us now move on to the non-inverting amplifier. We will first construct KCL at node D. Note that the voltage at D is equal to the source voltage by the definition of an ideal op-amp.

$$I_{R3} = I_{non,in1} + I_{R4}$$

$$\frac{V_o - V_D}{R_3} = 0 + \frac{V_D}{R_4}$$

$$V_o = \left(1 + \frac{R_3}{R_4}\right)V_D = \left(1 + \frac{R_3}{R_4}\right)V_s$$

Now we will construct KCL at node C:

$$0 = I_{o,2} + I_{R3} + I_{L2}$$

$$I_{o,2} = -I_{R3} - I_{L2}$$

$$I_{o,2} = -\frac{V_o - V_s}{R_3} - \frac{V_o}{R_L}$$

Thus, we have expressions for output voltage and current for each case. Noting that for a $\mu A741$ operational amplifier,

$$V_{OM} = \pm 14 [V], \text{ typical}$$

$$I_{OM} = \pm 40 [mA], \text{ typical}$$

and

$$P_L = \frac{V_o^2}{R_L}$$

We can use MATLAB to iterate through possible resistor combinations, ensuring that maximum output current and voltage specs are not exceeded, and storing maximum power outputs. See the code for additional details, but the resulting combinations are:

$$R_1 = 390 [\Omega], R_2 = 1.5 [k\Omega], R_3 = 5.6 [k\Omega], R_4 = 2 [k\Omega]$$

$$P_{inv} = 19.17 [mW]$$

$$I_{o,inv} = 10.62 [mA]$$

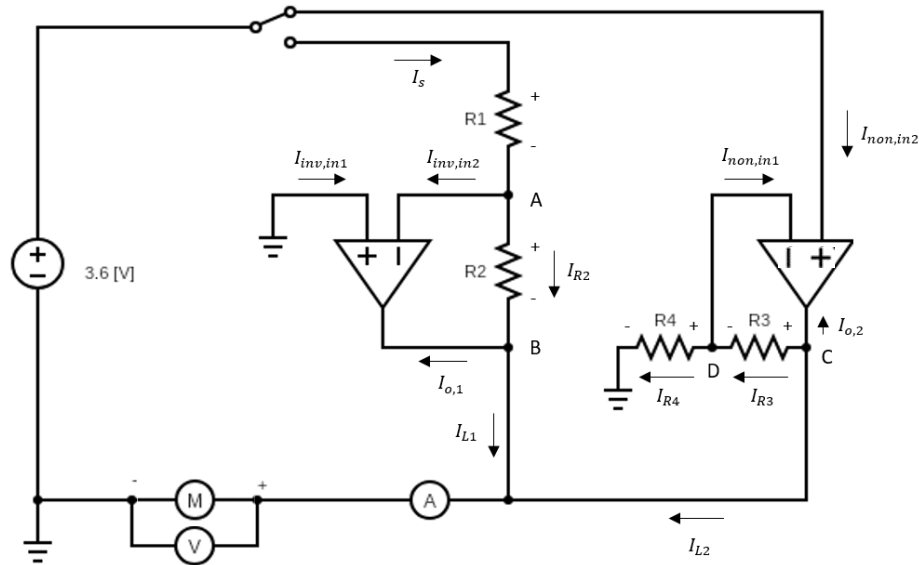
$$V_{o,inv} = -13.85 [V]$$

$$P_{non} = 18.17 [mW]$$

$$I_{o,non} = -3.17 [mA]$$

$$V_{o,non} = 13.68 [V]$$

Part 2: The circuit for part 2 is essentially the same as the circuit in part 1, only a motor replaces the 10 [kΩ] resistor:



Using the data from the specs for the motor, we see that the operating voltage for the meter is 3 [V] and the current at maximum efficiency is 0.175 [A]. Thus, we want the magnitude of the output voltage across the motor to be approximately 3 [V] and the load current to be about [0.175] mA. We can calculate the theoretical resistance of the motor as:

$$R = \frac{V_{motor}}{I_L} = \frac{3 [V]}{0.175 [A]} = 17.14 [\Omega]$$

Using the principle of a series voltage divider, we can calculate the necessary output voltage of the op-amps:

$$\left(\frac{17.14 [\Omega]}{47 + 17.14 [\Omega]} \right) V_o = 3 [V]$$

$$V_o = \pm 11.22 [V]$$

Recall from above the expressions for the output voltage and output current of the operational amplifiers:

$$V_o = -\frac{R_2}{R_1} V_s$$

$$I_{o,1} = -\frac{V_o}{R_2} - \frac{V_o}{R_L}$$

$$V_o = \left(1 + \frac{R_3}{R_4}\right)V_D = \left(1 + \frac{R_3}{R_4}\right)V_s$$

$$I_{o,2} = -\frac{V_o - V_s}{R_3} - \frac{V_o}{R_L}$$

Now, we must define our constraints. We must be careful to stay below the maximum output current of the op-amp, and we want the output voltage and current to be within reasonable bounds for the motor. It is left to the student to decide what appropriate limits are, but a sample set is given below:

$$10.80 [V] < |V_o| < 11.22 [V]$$

$$|I_o| < 185 [mA]$$

$$0.160 [A] < |I_L| < 0.180 [A]$$

See the MATLAB code for additional details. Possible combinations vary, but one possible solution that falls within the given parameters is:

$$R_1 = 33 [\text{k}\Omega], R_2 = 100 [\text{k}\Omega], R_3 = 5.6 [\text{k}\Omega], R_4 = 2.7 [\text{k}\Omega]$$

$$I_{L,inv} = -170.08 [\text{mA}]$$

$$I_{o,inv} = 170.19 [\text{mA}]$$

$$V_{o,inv} = -10.91 [V]$$

$$I_{L,non} = 172.54 [\text{mA}]$$

$$I_{o,non} = -173.87 [\text{mA}]$$

$$V_{o,non} = 11.07 [V]$$

Note that there are significantly more possible combinations for the non-inverting op-amp. This is because for the inverting op-amp, the currents add going into the op-amp, as opposed to splitting as with the non-inverting op-amp. This circuit will now allow you to alternate the direction of the DC motor.

The following diagram illustrates how the circuit will be wired. Note that for the OPA552 P Package, there is a safe operating area that gives the maximum output current as a function of the difference between the magnitude of the supply voltage across the op-amp and the output voltage of the op-amp. In order to ensure the op-amp max current is not exceeded, the voltage source should be set between ± 6 and ± 8 [V].

Budget:

Due to the nature of op-amps in general, we opted to invest in a tabletop power supply to ensure a consistent and accurate voltage reading at all times for a more predictable circuit performance. Along with that, we went for some banana-jack-to-mini-grabber wires to connect from the power supply to the breadboard. Students can use a small piece of wire with the ends stripped to connect the mini-grabber to the breadboard. We understand that this setup is far more expensive than using batteries, but it's also an investment in future classes. The power supply will last for a long time and can be applied to a plethora of projects, so this is only a one-time purchase and not every group needs their own.

Item	Link	Price
Breadboard	https://www.jameco.com/z/WBU-301-R-400-Point-Solderless-Breadboard-3-3-Lx2-1-W_20601.html	\$4.95
Banana jack to grabber wires	http://www.apogeekits.com/banana_grabber_test_leads.htm	\$3.95
Power supply	http://www.apogeekits.com/banana_grabber_test_leads.htm	\$59.99
DC motor	https://www.jameco.com/z/RF-500TB-18280-R-Nichibo-Taiwan-3-Volt-DC-Motor-2104-Rpm-1-3-Volt-Range_2158442.html	\$2.95
Jumper Wires	https://www.jameco.com/z/ZW-MM-20-Busboard-Prototype-Systems-ZipWire-40-Piece-20cm-Male-to-Male-Colored-Jumper-Wires_2260738.html	\$4.95
Op amps	https://www.mouser.com/ProductDetail/Texas-Instruments/OPA552PA?qs=sGAEpiMZZMtCHixnSjNA6Mrdwin7F8A2x1kwI3sDiuw%3D	2*\$4.70
Resistor assortment	https://www.jameco.com/z/ASST8-R-E12-Resistor-Pack-1-4-Watt-5-350-Pcs-70-Values-10-to-5-6M-Ohm_10720.html	\$9.95
Switch	https://www.jameco.com/z/SS-12E17-3-Pin-SPDT-Slide-Switch_2258831.html	\$0.69
Batteries	here	\$8.95

In total, a single project adds up to cost \$105.78, but we really must keep in mind that resistor assortment packs, breadboard, jumper wires, batteries, switch, power supply & cables, are all usable for an entire semester and more. The motors and op amps would obviously also still be usable, though may be used significantly less frequently.

Conclusion:

Op amps can be a difficult concept to master, but through this project students are exploring both the inverting, and noninverting type. First in maximizing the power output across a load, and then in acting as a directional control for the DC motor. The first part of the circuit is done theoretically, while the second is physically built. The MATLAB requirement teaches students how to iterate through a large number of resistor values efficiently and precisely. The total cost of the project with every component including the power supply is \$105.78.

Summary of Work

Both:

- Ideation and project development

Frank: 50%

- Schematics
- Part 1 and 2 solution analysis

Katie: 50%

- Executive summary
- Budget
- Conclusion