**Lab 6A: Op amp part 1 – voltage follower, current limitation**

**Objectives**

1) Become familiar with setting up a basic op amp circuit, including pin assignment and voltage rails.

2) Investigate the loading effect of a voltage divider, and using a buffer circuit to deal with the issue.

3) Investigate the limitation of the op amp output current.

**Background**

An operational amplifier (op amp) is a dependent source (VCVS type). It has three sets of connections.

1) A pair of positive and negative **signal inputs**, non-inverting input Vin+ (pin 3) and inverting input Vin- (pin 2). The difference of these two inputs (i.e., Vd = Vin+ – Vin-) produces a differential input Vd to the op amp.

2) A single **signal output** Vout (pin 6).

3) A pair of positive (pin 7) and negative (pin 4) **voltage rails** to power the op amp.

Diagram, schematic

Description automatically generated

The op amp has the following important characteristics:

1) Very high open-loop gain A: Vvcvs = A\*Vd = A\*(Vin+ – Vin-), where A is very large ( up to ~105).

2) Very high input (MOhm) impedance (resistance) Rin (Ri), thereby causing Iin+ ≈ 0; Iin- ≈ 0.

3) Very low (several Ohms) output impedance/resistance Rout (Ro), thereby causing Vout ≈ Vvcvs for regular load RL (usually in kOhm range).

4) Closed-loop gain depends on the resistor negative feedback network that is external to the op amp.

The above point 1 means that the op amp by itself can provide very high amplification (gain), as high as several thousand to hundreds of thousands. This also means that, when the op amp is not saturated (i.e., not being driven to its maximum or minimum output values), it is a mathematical certainty that the input Vd = Vin+ − Vin- ≈ 0, which means Vin+ ≈ Vin-. This non-saturated region of operation is called the linear operating region of the op amp.

Point 2 means that, for practical purposes, no meaningful amount of current may enter the op amp’s two signal inputs (pin 2 and pin 3).

Point 3 means that the op amp’s output voltage Vout is not meaningfully affected by output current Iout that flows out of the op amp and into the load resistor. To be sure, the voltage division rule still applies to the op amp’s output resistor Rout and the load resistor RL, but since Rout is only a few Ohms whereas RLoad is typically several kOhms, almost all of the VCVS’s output A\*Vd is distributed to Vout, which is the voltage across the load RL.

Point 4 means that when there is a closed loop between the output (pin 6) and the inverting signal input (the Vin- input, pin 2) of the op amp, a negative feedback loop exists. The gain of the op amp circuit will be primarily determined by the external resistor network outside the op amp.

An op amp has the following primary **limitations**. You are probably familiar with the first two limitations, which you will investigate in Labs 6A and 6B. Investigation of the third and fourth limitations (slew rate and bandwidth) are optional.

1) Vout has upper and lower limits, which are slightly less than (about 1V less than) the op amp’s positive and negative power rail voltages (typically ± 15V).

2) Iout of the op amp has a saturation limit, usually about 20 mA to 40 mA.

3) The rate of change of Vout has a limit, which is typically about 0.5V/μs. This is the op amp’s **slew rate**, and is determined primarily by the op amp’s internal capacitance.

4) For a high frequency AC input to the op amp, the op amp’s output voltage has a saturation level. This is the op amp’s **bandwidth** limitation, and is primarily determined by the op amp’s internal capacitance.

**Procedure**

**Part 1: first op amp circuit – buffer/voltage follower**

Part 1a: setting up a simple op amp buffer circuit with negative feedback

Construct the following op amp buffer circuit

Diagram, schematic

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**Avoid mistake:** Refer to the LM741 op amp spec sheet, especially the op amp’s pin assignment (also introduced on the previous page). I**ncorrect connection may destroy the op amp and cause explosion!**

**Explain:** For the power supply Rigol DP832, it is a good idea to use its Channel 1 for the -15V power rail of the op amp. Channel 2 is not a good option to provide the negative voltage rail. Explain why.

**Measure and plot:** Change the signal source voltage Vs to have at least 10 values spanning from -15V to 15V, measure output voltages, and **plot** the **voltage transfer curve (VTC)** Vout vs. Vin

**Tricky issue:** The power supply Rigol DP832 Channel 3 only goes up to 5V, so you can’t use it to obtain Vs to range from -15V to 15V. What then is your solution? Hint: recall potentiometer applications

**Explain:** Why is this circuit also called a voltage follower?

**Observe:** Is there nonlinearity in the transfer function Vout/Vin? Explain.

Part 1a data table:

|  |  |
| --- | --- |
| Plot the VTC of the op amp voltage follower |  |
| Why is this circuit called a voltage follower? |  |
| Explain the nonlinearity near the ends of the VTC |  |

Part 1b: using buffer/voltage follower to eliminate **loading effect**

Construct the following two circuits to explore the loading effect of a classic voltage divider, and using an op amp to overcome this loading effect. The top circuit is a classic voltage divider and its load RL1. The bottom circuit has an op amp buffer that isolates a classic voltage divider from its load RL2.

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Build the top circuit to explore the loading effect of a classic voltage divider.

1. Without attaching the load RL1, measure Vout1. Verify that the output voltage Vout1 conforms to voltage division rule (VDR).
2. Now attach the load RL1 to the Vout1 node and measure Vout1 again. What is Vout1 after attaching this 1k load?
3. Why can you no longer obtain the intended Vout1 (about 2V) from this classic voltage divider? This limitation of the classic voltage divider is a type of loading effect.

Build the bottom circuit to explore using the op amp buffer to overcome the loading effect.

1. Measure the output voltage Vout2 before and after attaching the load RL2 to the output node Vout2. How different are these two Vout2 values?
2. How does the voltage follower (buffer) overcome the loading effect limitation of a classic voltage divider? (Hint: what is the resistance of the buffer as seen from the Vin node?)

Part 1b data table:

|  |  |
| --- | --- |
| **Classic voltage divider circuit** | |
| Without attaching the load, what is Vout1? |  |
| After attaching the load, what is Vout1 |  |
| Why does VDR no longer work after attaching the load? |  |
| **Op amp buffer circuit** | |
| Without attaching the load, what is Vout2? |  |
| After attaching the load, what is Vout2? |  |
| How does the op amp buffer overcome the loading effect? |  |

**Part 2: current limitation (saturation) of op amp**

Construct the following voltage-follower circuit (very similar to the circuit of part 1a, so you may reuse part of the circuit in part 1). The signal input voltage Vs is maintained at 2V. Use a decade box R1 as the load of the output node Vout. Using the decade box lets you easily vary the load resistance RL.

Diagram, schematic

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**Measure and sketch:** Starting with the load resistance RL at 1k, measure the load voltage Vout and the load current ILoad. Then decrease the load resistance (at 0.1k intervals), and repeat the voltage and current measurements. Record and plot Vout vs. RL, and ILoad vs. RL.

**Observe:** At what load does the voltage follower circuit stop working properly (i.e., Vout stops following Vin)? What is the op amp output current ILoad at this point?

(For example: at 0.5k RL, you may see the load current rapidly increasing to 12mA, so Vout is no longer 2V; as RL decreases further, the load current ILoad further increases until it saturates)

**Measure:** What is the maximum output current (current limit) of this op amp?

When this op amp reaches its output current limit, why will it no longer function as a voltage follower?

Part 2 data table:

|  |  |
| --- | --- |
| Plot Vout vs. RLoad to show what happens with Vout when RLoad is too small. |  |
| Plot I\_Load vs. RLoad to show what happens with I\_Load when RLoad is too small. |  |
| At what load does the voltage follower stop working properly? |  |
| What is the op amp output current at this point? |  |
| What is the maximum output current (current limit) of this op amp? |  |
| When this op amp reaches its output current limit, why will it no longer function as a voltage follower? |  |

**Data tables and scope image captures**

Part 1a data table:

|  |  |
| --- | --- |
| Plot the VTC of the op amp voltage follower |  |
| Why is this circuit called a voltage follower? |  |
| Explain the nonlinearity near the ends of the VTC |  |

Part 1b data table:

|  |  |
| --- | --- |
| **Classic voltage divider circuit** | |
| Without attaching the load, what is Vout1? |  |
| After attaching the load, what is Vout1 |  |
| Why does VDR no longer work after attaching the load? |  |
| **Op amp buffer circuit** | |
| Without attaching the load, what is Vout2? |  |
| After attaching the load, what is Vout2? |  |
| How does the op amp buffer overcome the loading effect? |  |

Part 2 data table:

|  |  |
| --- | --- |
| Plot Vout vs. RLoad to show what happens with Vout when RLoad is too small. |  |
| Plot I\_Load vs. RLoad to show what happens with I\_Load when RLoad is too small. |  |
| At what load does the voltage follower stop working properly? |  |
| What is the op amp output current at this point? |  |
| What is the maximum output current (current limit) of this op amp? |  |
| When this op amp reaches its output current limit, why will it no longer function as a voltage follower? |  |