ENGG 225

Fundamentals of Electrical Circuits and Machines

Laboratory #3

Operational Amplifier Circuits

1 Introduction

The operational amplifier ("op-amp") is an electronic circuit developed by Fairchild Semiconductor Corportation in 1966. The op-amp enjoys a large number of diverse applications, from sensitive measurement circuits to microelectronic communications circuits. The op-amp is a complex circuit composed of transistors and resistors, and is constructed on a single piece of silicon and packaged as an integrated circuit (IC). Op-amp ICs are used in circuits with other resistors (and sometimes capacitors) to do many important and interesting things.

1.1 Learning Outcomes

At the end of this laboratory session, you will be able to design and test some important and common amplifier configurations, and to experiment with a practical pulse-rate measurement circuit. Specifically, you will:

- learn to analyze and test a non-inverting amplifier circuit;
- to develop an understanding of important fundamental properties and limitations of an op-amp;
- learn to design and test an inverting summing amplifier circuit;
- design and test an amplifier and voltage comparator circuit to measure a human heart rate.

1.2 UCEE Acknowledgment

The course instructors for ENGG 225 greatly acknowledge the University of Calgary Engineering Endowment (UCEE) Fund for substantial funding toward the purchase of important high-quality laboratory test equipment and supplies needed to enhance the learning value of the laboratories in the course.

2 Background Review

2.1 Simple Amplifier Configurations

An op-amp is a differential amplifier circuit with a very high *open-loop* gain, A. Although not directly useful on its own, the op-amp is mostly used in circuits designed to utilize negative feedback. Some of the circuits that we have investigated are the *inverting amplifier* shown in Fig. 1 and the *non-inverting amplifier* shown in Fig. 2.

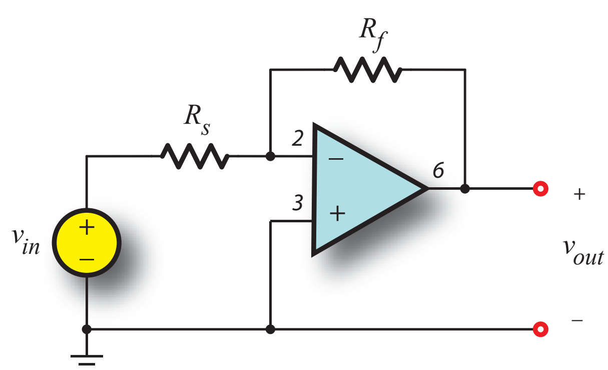

Fig. 1. The inverting amplifier configuration

For each of these amplifier configurations, we define the *closed-loop gain*, A_v, as

$$A_v = \frac{v_{out}}{v_{in}}. \tag{1}$$

Assuming ideal op-amps and negative feedback, A_v can be derived by analyzing each circuit using the *summing-point constraints* imposed at the op-amp's input terminals.

A slight variation of the inverting amplifier is the *inverting summing amplifier* shown in Fig. 3. Such a circuit is capable of adding two or more voltages, and can be analyzed in the same way as the simple inverting amplifier.

2.2 A Comparator Circuit

Another very useful application of op-amps is in a voltage *comparator* circuit. Here, the op-amp is operated *open-loop*; that is, negative feedback is not employed. The

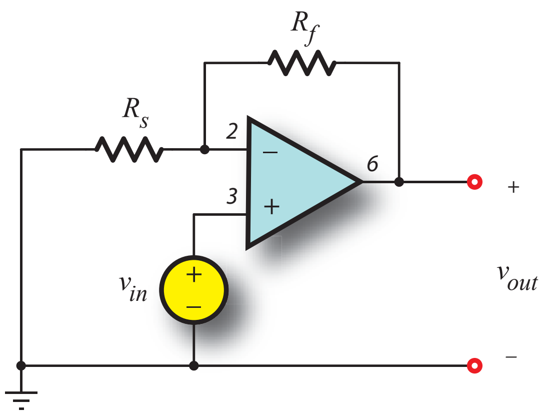

Fig. 2. The non-inverting amplifier configuration

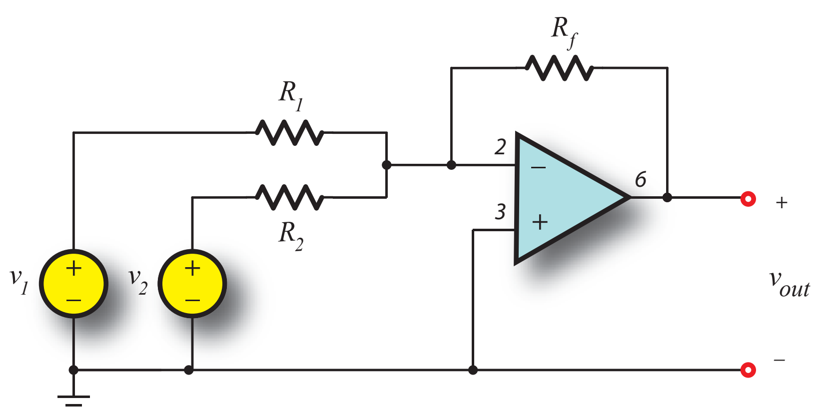

Fig. 3. The inverting summing amplifier configuration

comparator compares two voltages, and produces one of exactly two possible output voltages depending on the result of the comparison.

A very simple comparator circuit is shown in Fig. 4, and consists simply of an op-amp and a voltage source. This circuit is designed to test the *sign* of the input voltage v. With the op-amp operating open-loop like this, the output voltage is given simply by

$$v_{out} = -A\,v, \tag{2}$$

where A is the open-loop gain for op-amp, and is a huge number (typically, $A > 10^5$). Since the op-amp cannot produce a voltage at its output that is larger in amplitude than its external power sources allow, the op-amp *saturates* at either $+V_{CC}$ or $-V_{EE}$, so v_{out} will be:

$$v_{out} = \begin{cases} -V_{EE}, & v > 0 \\ +V_{CC}, & v < 0 \end{cases} \tag{3}$$

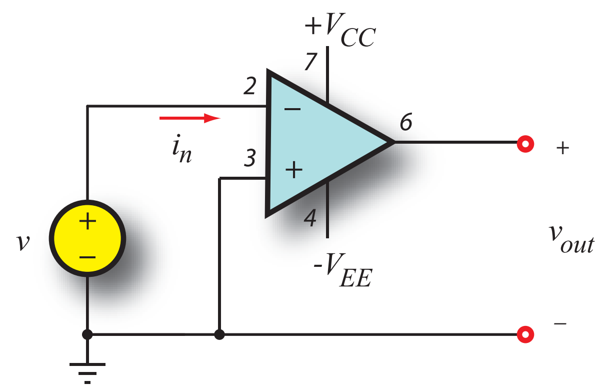

Fig. 4. A Voltage Comparator Circuit

The huge value of A in equation (2) ensures that even *tiny* positive and negative values of v cause the op-amp to saturate in this way.

3 Pre-Lab Exercises

The pre-lab work must be completed prior to the laboratory session and will be checked prior to beginning the experimental exercises.

3.1 The non-Inverting Amplifier

1. Derive an expression for v_{out} in terms of R_s, R_f, and v_{in} in Fig. 2.
2. Calculate v_{out} when $R_s = 2.2K\Omega$, $R_f = 1K\Omega$, and $v_{in} = 5$ V. Determine the closed-loop gain A_v.
3. Repeat step 2 with a $1K\Omega$ resistor connected from the output of the op-amp at v_{out} to the reference node.
4. Repeat step 2, this time with $R_f = 8.2K\Omega$.

3.2 The Inverting Summing Amplifier

Design the inverting summing amplifier in Fig. 3 by choosing resistor values R_1, R_2, and R_f to meet the following specifications:

- the voltage gain $A_{v_1} = v_{out}/v_1 =$ -10.85.
- the voltage gain $A_{v_2} = v_{out}/v_2 =$ -0.667.
- the values of R_1, R_2, and R_f must *not be less than* $4.7K\Omega$. The available resistors are listed in Table I. Use resistor combinations if necessary.

Table I - Available Resistors

100 Ω	390 Ω	1 $K\Omega$	8.2 $K\Omega$
120 Ω	470 Ω	1.2 $K\Omega$	10 $K\Omega$
220 Ω	680 Ω	2.2 $K\Omega$	51 $K\Omega$
330 Ω	820 Ω	4.7 $K\Omega$	100 $K\Omega$

4 Procedure

One report per group is required, and must be completed during the lab session.

In all parts of the experiment below, it is necessary to physically connect $+V_{CC}$ and $-V_{EE}$ to pins 7 and 4, respectively, on the op-amp. This supplies power to the op-amp's internal circuitry. Use the +15 V source built into the breadboard for V_{CC}, and the -15 V source for $-V_{EE}$. These sources will also be used to power the Dual Audio Buffer module (Fig. 7).

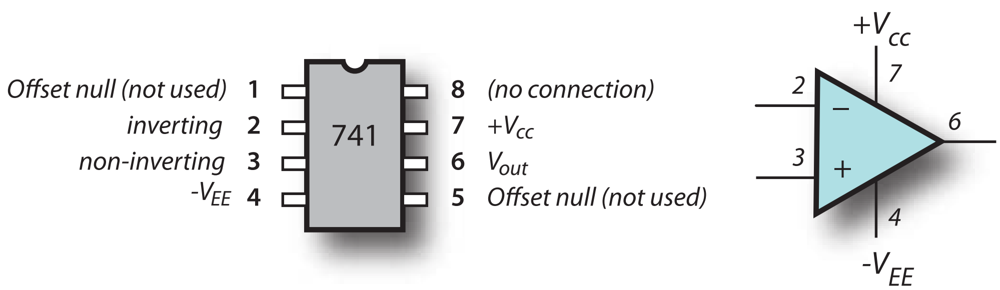

Fig. 5. Type 741 op-amp pin layout

The pin layout for the type-741 op-amp is shown in Fig. 5. The op-amp should be placed onto the breadboard such that the middle of the op-amp straddles the divider between two sections on a Type-1 socket strip on the breadboard. Orientation of the IC is very important. By convention, pin 1 is always to be in the upper-left corner. Pin 1 is identified by either a small dimple beside it, or a small "bite" out of the nearby top edge (as illustrated in Fig. 5). A correctly installed IC is shown in Fig. 6. Making connections to the IC is very easy by using any of the 4 available holes adjacent to each IC pin, as shown.

4.1 The Non-Inverting Amplifier

1. Construct the non-inverting amplifier circuit shown in Fig. 2 using the values $v_{in} = 5$ V, $R_f = 1K\Omega$, and $R_s = 2.2K\Omega$. Use the 5 V source on the breadboard.

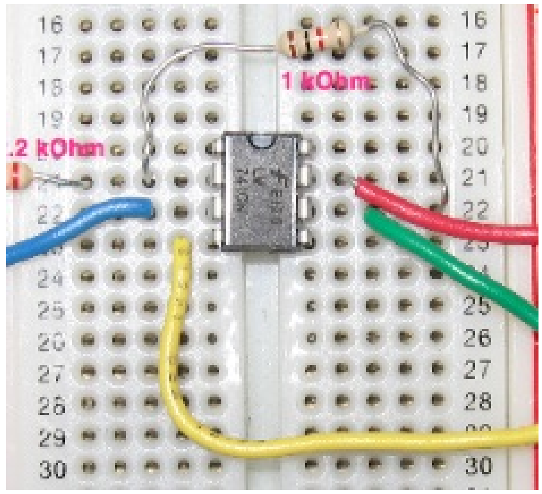

Fig. 6. Breadboard placement of IC with sample connections

2. Measure the output voltage using the DMM and compare this value to that predicted in the pre-lab exercises.

3. Connect a $1K\Omega$ resistor between v_{out} and the reference node. Re-measure the voltage v_{out}, and compare with v_{out} calculated in the pre-lab exercises. Does the voltage change? Why or why not?

4. Remove the $1K\Omega$ output resistor in step 3, and replace R_f with a $8.2K\Omega$ resistor. Re-measure the voltage v_{out}, and compare with that calculated in the pre-lab exercises. Are they significantly different? Why or why not?

5. In the following steps, you will measure the "summing-point constraints" and observe how closely the type-741 op-amp resembles the ideal op-amps that we have been studying in lectures. For this part, use $R_f = 1K\Omega$.

   (a) Measure and record the current entering the op-amp at the non-inverting terminal (pin 3). Do this by breaking the connection between the positive terminal of the 5 V source and pin 3 of the op-amp. Connect the DMM between these two points (with the DMM's + terminal (red) connected to the source.) Is this value what you expect? Briefly explain.

   (b) Replace the connection between the voltage source and pin 3 of the op-amp in part (a). Now set the DMM to measure voltage, and measure the voltage between the op-amp's input terminals (pins 2 and 3). Is this value what you expect? Briefly explain.

4.2 The Inverting Summing Amplifier

In this part, you will explore the inverting summing amplifier in a practical application involving a human heartbeat signal. The signal has been pre-recorded using a piezo-electric sensor to detect the heartbeat of one of your course instructors. The sensor detects the pulse from the blood pressure variations in the arteries of a finger, and produces a relatively weak signal with voltages in the 100-200 mV range. You will build the summing amplifier to:

- amplify this signal to a more practical voltage range;
- add a variable amount of DC offset to this signal to permit heartbeat detection using a simple comparator circuit and a Light-Emitting Diode (LED).

The circuit is to be built in two main stages. The first is to build an inverting amplifier circuit, and test it using the pre-recorded heartbeat signal. The second is to use the same circuit to add a DC offset to the heartbeat signal, and to build the simple comparator circuit.

4.2.1 Viewing the pre-recorded heartbeat signal

The pre-recorded heartbeat signal is available to your circuit through the audio-output jack on the PC at your lab station and the *Dual Audio Buffer module* shown in Fig. 7. Before building your circuit, set up and test the PC and buffer as follows.

Fig. 7. The Dual Audio Buffer used to interface with PC audio output.

1. Connect the three power connections (+15 V, GND, -15 V) from the breadboard to the banana connections on the buffer module.
2. At each lab station, a grey-coloured audio patch cable is plugged into the audio-output jack at the rear of the PC. The other end of this cable is routed up to

reach your breadboard, and should be visible near the equipment sled. Attach the connectors on this cable to the “Right Input” and “Left Input” on the buffer module. A fully wired buffer module is shown in Fig. 8.

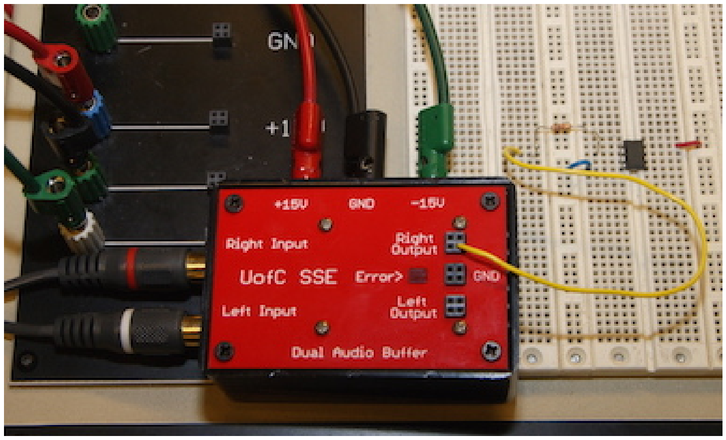

Fig. 8. The Dual Audio Buffer shown with power-supply connections (top), audio inputs (left), and connection to your circuit (right).

3. On the PC at your lab station, navigate in Windows 7 to the network drive **N:** and locate the folder `ENGG` and subfolder `225` and `Lab3`. There will be an audio file named `Heartbeat.wav`. Double-click on it to play it through the PC’s audio output. On the PC, the volume settings should be at their highest levels. For convenience, have the Windows Media Player play the audio file in a continuous loop.

All measurements on your circuit will be made using an oscilloscope probe, such as that shown at right. This is the first time you’ve used one of these in the ENGG 225 labs. You will find two such probes already attached to the oscilloscope’s Channel 1 and Channel 2 inputs. Measurements on your circuit are made by squeezing the probe end to expose a small “hook” which can easily connect to a wire or component in your circuit. Connect the black alligator clip to any handy ground connection on the breadboard (i.e., anything green!).

Use the Channel 1 probe to connect to either of the “Left Output” or “Right Output” sockets on the Buffer with a short wire. Make the following adjustments *manually* to properly view the waveform on the oscilloscope display.

1. Adjust the **vertical scale** (volts/division) control until the setting shown in the top-left corner of the display indicates 100 mV/division. The vertical-scale knob is the one immediately above the illuminated "1" button. You may adjust the **vertical position** of the waveform with the knob just below the "1" button.

2. Adjust the **time-scale** control (upper-left corner of the oscilloscope controls) until the setting at the top of the display shows 200 msec/division. You should be able to see two or three heartbeat pulses on the oscilloscope display.

- Make a sketch of this waveform as best you can on graph paper in your notebook record. Record the voltage scale and time scale on your sketch.

4.2.2 Amplifying the heartbeat signal

Construct the circuit in Fig. 3 using resistor values from your pre-lab design work. For now, *do not* connect source v_2 (i.e., leave the left side of R_2 open-circuited). For v_1, use the output of the Dual Audio Buffer (either the left or right channels); to do this, disconnect the oscilloscope probe from the buffer, and connect the output of the buffer to R_1 in the circuit with a wire.

Now connect the oscilloscope probe to v_{out} in the circuit. Manually adjust the vertical scale on the oscilloscope until the amplified waveform becomes fully visible again (remember that the amplitude of v_{out} will be almost 11 times larger than v_1).

- Make a sketch of v_{out} on graph paper in your notebook record, and again record the voltage and time scales. Other than the amplitude being significantly different from your previous sketched waveform, what other key feature of the waveforms are different?

4.2.3 Adding the DC offset with a potentiometer

Following the steps below, connect the v_2 source to the inverting summing amplifier to add a DC offset to the amplified heart signal.

Located in the bottom-right portion of the breadboard are three built-in variable resistors, called *potentiometers* (or "pots" for short). They are resistors with a fixed resistance between their endpoints, and have an adustable "wiper" that makes an electrical connection to the resistor at some point between. You will use this as an adjustable voltage divider simply by twisting the potentiometer's control knob.

IMPORTANT: *Be VERY sure to use the* $10K\Omega$ *potentiometer in the steps below. If you instead mistakenly connect the* $1K\Omega$ *potentiometer, there will sure to be smoke (and very angry technical staff)!*

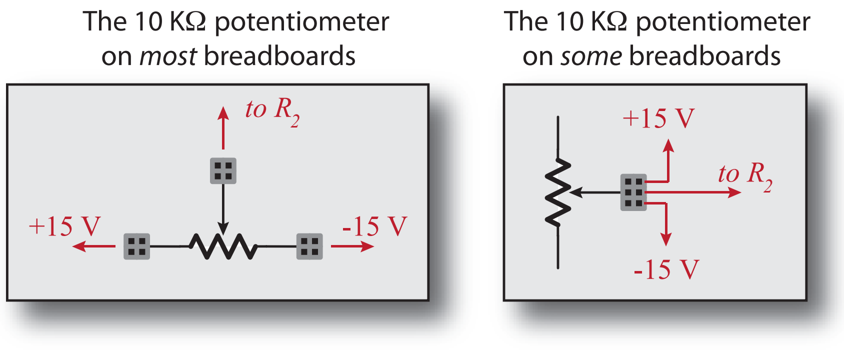

Fig. 9. 10KΩ *potentiometers on the ENGG 225 breadboards.*

As indicated in Fig. 9, connect the endpoints of the 10 KΩ potentiometer to the +15 V and -15 V sources on the breadboard. Connect the adjustable "wiper" to R_2 of your inverting summing amplifier. This will be v_2.

With the oscilloscope probe still connected to v_{out} in the inverting summing amplifier, carefully and *gently* adjust the potentiometer to move the heartbeat waveform to a vertical position on the oscilloscope display where only the bottom peaks of the waveform are negative in value. At the very left edge of the oscilloscope display is a small ground symbol indicating the zero-volt reference to assist you.

4.2.4 Building the comparator and LED output

Finally, use a second op-amp chip to build the simple comparator circuit in Fig. 10. *(Remember to power the chip with* $\pm$15 V*!)* The input to this circuit is v_{out} from the inverting summing amplifier. If all is working correctly, the LED should flash once every heartbeat.

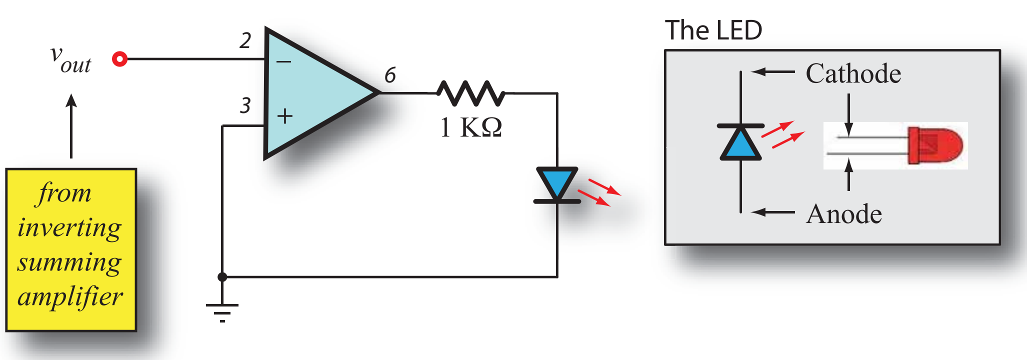

Fig. 10. The heart monitor circuit