Başkent University
Department of Electrical and Electronics Engineering

EEM 311 Electronics II

Experiment 9

OPERATIONAL AMPLIFIERS

Objectives:

1.To demonstrate an inverting operational amplifier circuit.

2.To demonstrate the use of operational amplifiers for performing mathematical operations –integration and differentation.

Discussion:

The operational amplifier is probably the most frequently used linear integrated circuit available. Applications for operational amplifiers range from the simple voltage amplifiers discussed in this experiment to complex circuitry that is beyond the scope of this course. The amplifier configurations investigated in this experiment are the basic building blocks of modern electronic circuits. There are two basic configurations for operational amplifier circuits: the inverting amplifier and the noninverting amplifier. Operational amplifiers ideally have infinite open-loop gain and infinite open-loop input resistance. Open-loop characteristics refer to those of an amplifier having no feedback resistance between output and input. Closed-loop characteristics are those of an amplifier having an external feedback resistor. The resistor provides negative feedback, whereby a portion of the output voltage is subtracted from the input. Both the inverting and noninverting amplifier use the principle of negative feedback to control the overall (closed-loop) voltage gain. Figure 1 shows a typical inverting amplifier configuration. An ideal inverting amplifier's voltage gain is determined by:

$$A = -\frac{R_F}{R_1}$$

where:

R_1 is the input resistor
R_F is the feedback resistor
As usual, the minus sign signifies phase inversion.

As shown in Figure A, the output of an electronic integrator is proportional to the total area under the input waveform up to that point in time. To perform integration, a capacitor is connected in the feedback path of the amplifier. However, any DC voltage appearing at the input of an integrator will cause the output voltage to rise (or fall) until it reaches its maximum (or minimum) possible value. To prevent this undesirable occurence, a ressitor, R_F, is connected in parallel with the feedback capacitor. Any DC input voltage, such as the input offset voltage of the amplifier, is then simply amplified by the DC gain, R_F/R_1.

The following equation can be used to determine the output voltage of the op-amp integrator with a sine wave input:

$$V_O = \frac{-1}{R_{in}C_F} \int V_{in}\, dt = \frac{-1}{R_{in}C_F} \int A \sin(\omega t)\, dt = \frac{-1}{(\omega R_{in}C_F)} A \cos(\omega t)$$

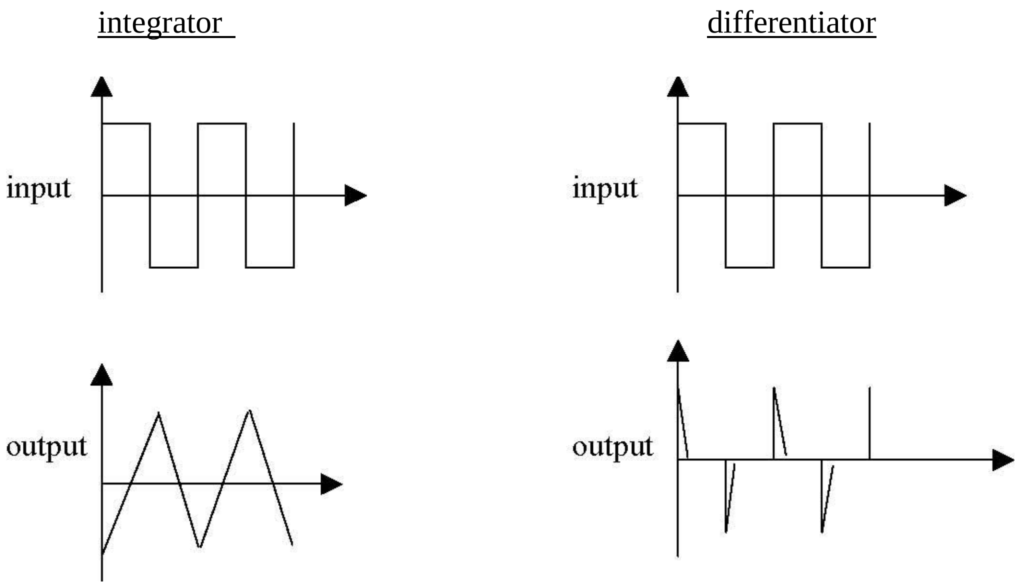


Figure A

Integration will be performed only at frequencies well above the break frequency caused by the feedback resistor:

$$f_B = \frac{1}{2\pi R_F C_F} \qquad \text{(break frequency for integrator)}$$

As shown in Figure A, the output of an electronic differentiator is proportional to the rate-ofchange of input waveform at any point in time. To perform differentiation, a capacitor is connected in series with the input. The following equation can be used to determine the output voltage of the op-amp differentiator with a sine wave input:

$$V_o = -R_F C_{in} \frac{dV_{in}}{dt} = -R_F C_{in} \frac{dA \sin(\omega t)}{dt} = -(\omega R_F C_{in}) A \cos(\omega t)$$

Since the output voltage of a differentiator is proportional to the input frequency, high- frequency signals (such as electrical noise) may saturate or cutoff the amplifier. For this reason, a resistor is placed in series with the capacitor in the input. This establishes a high-frequency limit beyond which differentiation no longer occurs:

$$f_B = \frac{1}{2\pi R_{in} C_{in}} \qquad \text{(break frequency for differentiator)}$$

To achieve greater attenuation at higher frequencies (to prevent oscillation), a feedback capacitor is added in parallel with the feedback resistor. This establishes another break frequency that can be calculated like the one in the integrator.

Procedure:

1. To investigate an operational amplifier used as an inverting amplifier, connect the circuit in Figure 1.The small numbers in the diagram correspond to the integrated circuit's (chip's) pin numbers, as shown in specification sheets. (NOTE: If oscillation occurs it may be necessary to add 0.1 μF capacitors from each supply pin to ground. Also keep this in mind when performing all future op-amp experiments.)

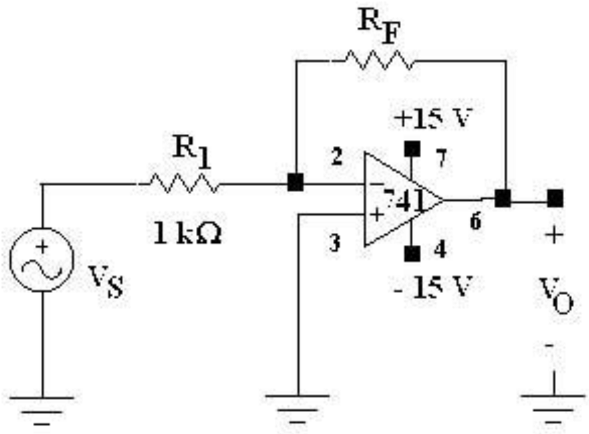


Figure 1

2. Connect a dual-trace oscilloscope to observe both the input V_S =100 mVp @ 1 kHz, and the output voltage V_O draw the input and output waves in report . Also note ,for an indicated value, the phase angle of the output V_O with respect to the input V_S. (Use a 4.7 KΩ resistor for R_F for this step)

3.To verify that the inverting amplifier is a dc amplifier, replace the signal generator with a dc power supply. With R_F =10kΩ, and V_S =1 VDC measure the output voltage V_O and note its polarity with respect to V_S.

4.Now replace R_F with a 1 MΩ resistor and sketch the resulting output waveform V_O as well as the input waveform V_S. What is your comment for that situation.

5.To investigate the use of an operational amplifier to perform mathematical integration, connect the circuit in Figure 2.

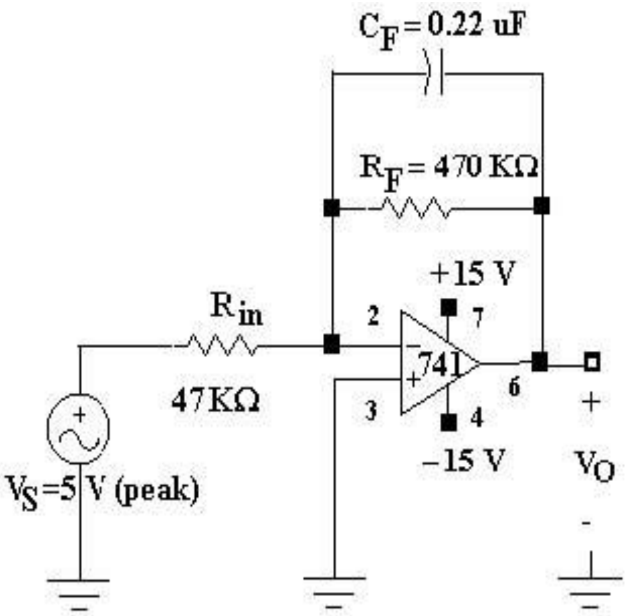


Figure 2

6. With Vs adjusted to produce a ± 5 V peak square wave @ 100 Hz. Using a dual-trace oscilloscope, sketch the output voltage Vo graph and the input voltage Vs graph to the report –indicated values must be shown on graph-

7.Find break frequency, f_B for integrator which is formulated in discussion part. Change the frequency to 20 Hz, what happens? Then change the frequency to 1 KHz, what happens?

8.To investigate the use of an operational amplifier to perform mathematical differentiation, connect the circuit in Figure 3.

9.With Vs adjusted to produce a ± 1 V peak square wave @ 200 Hz. Using a dual-trace oscilloscope, sketch the output voltage Vo graph and the input voltage Vs graph to the report –indicated values must be shown on graph-

10. Find break frequency, f_B for differentiator which is formulated in discussion part. Change the frequency to 500 Hz, what happens? Then change the frequency to 100

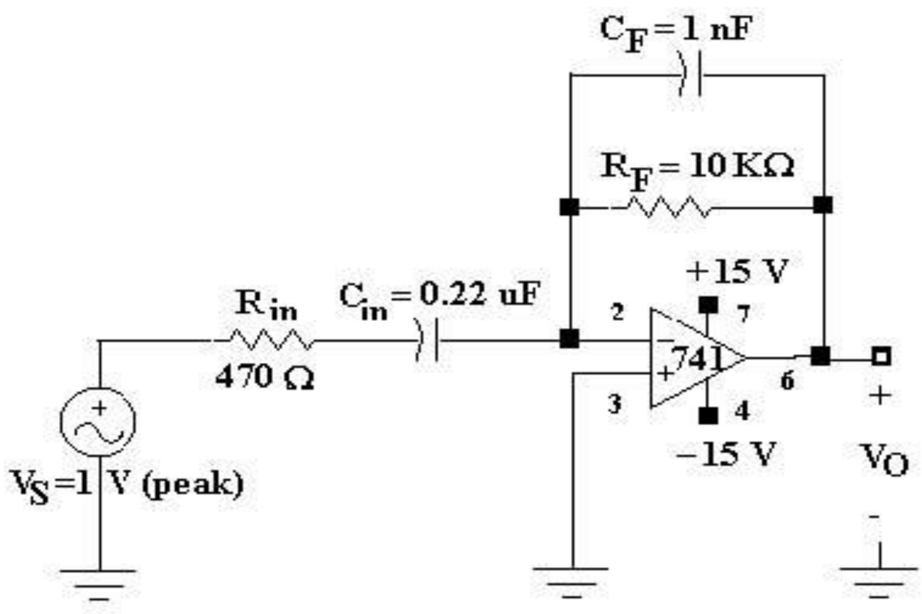


Figure3

<u>Questions:</u>

1.What are the results of integrator and differentiator op-amp circuit experiments. Do they really work?
2.What is the phase difference between Vs and Vo for an inverting op-amp circuit

Equipment List:

- 741 operational amplifier or the equivalent
- DC power supplies (±15V and variable)
- Analog signal generator
- Resistors: 1*1MΩ, 1*4.7 kΩ, 1*10 kΩ, 1*1 kΩ, 1*47 kΩ, 1*470 kΩ, 1*470 Ω
- Capacitors: 1*1 nF, 1*0.22 μF
- Dual-trace oscilloscope

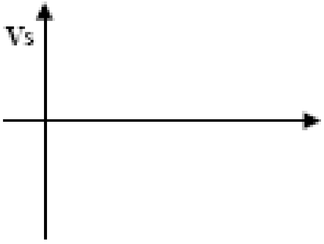
References:

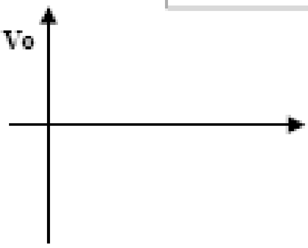
Electronic Devices and Circuits, Fifth Edition: Section 10-1, The Ideal Operational Amplifier.

REPORT:

Name, Surname:
ID # :

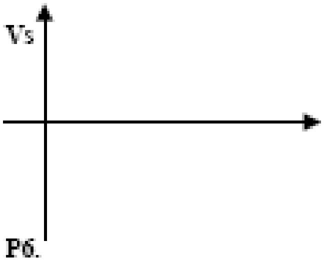
P2.
For inverting op-amp

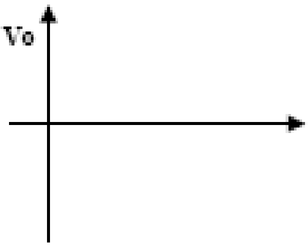




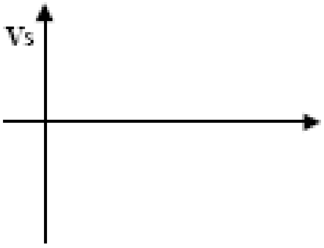
P3. With R_F =10kΩ, and V_S =1 VDC V_O=.........

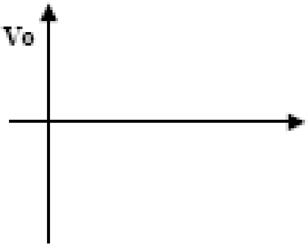
P4.
For inverting op-amp (with R_F = 1 MΩ) **comment:**





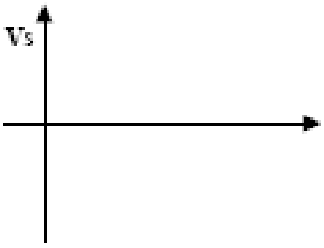
P6.
For integrator op-amp

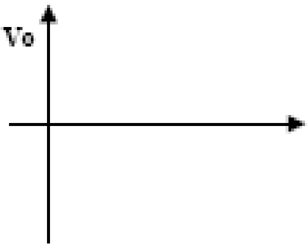




P7. f_B=....... **comment:**

P9.
For differentiator op-amp





P10. f_B=....... **comment:**

Q1. Q2.

OP-AMP CHARACTERISTICS AND INSTRUMENTATION AMPLIFIERS

Objectives:

The purpose of this experiment is to give you experience in working with instrumentation amplifiers and to learn how to obtain some characteristics of operational amplifiers (op-amp) such as slew rate, common mode rejection ratio, bandwidth, offset voltage..

IMPORTANT!!! Understood all is a must! You must also declare the equipment list that you will use in your design to the teaching assistant at least one hour before the laboratory experiment. Make groups by at most 3 persons. In the lab your whole questions may not be answered. (Download the LM741 & AD620 data sheet from internet to look at it in a need.)

Discussion:

The op-amp has a few limitations. This experiment will investigate the op-amp's bandwidth as a function of gain, the slew rate of op-amp and output offset voltages. Unlike a real op-amp, the ideal op-amp has an infinite voltage gain, perfectly matched internal resistors, and no output offset voltage. The bandwidth of an op-amp is inversely proportional to the closed-loop gain of the amplifier. The following equation shows the relationship between bandwidth and the feedback ratio, β:

$$fT=BWCL/\beta$$

where: fT is the gain bandwidth product or unity gain frequency
BWCL is the closed loop bandwidth of the amplifier
β is the feedback ratio:

$$\beta=R1/(R1+RF)$$

Another factor that limits the high frequency response of an op-amp is its maximum permissible slew rate. The maximum slew rate is the maximum value of :

$$S=\Delta V/\Delta t$$

where:ΔV is a change in output voltage Δt is the tim internal over which the output voltage changes
The slew rate limits the high frequency response because at high frequencies, there is a large rate of change of voltage. The maximum sinusoidal frequency at which an op-amp having a slew rate S can be operated without producing distortion is:

$$fS(max) = S/2\pi K$$

where: fS(max) is the maximumfrequency imposed by the slew rate limitation K is the peak value of the output waveform

Output offset voltage is the DC voltage that appears at the output when both inputs are zero volts. The output offset voltage of an op-amp is caused by input offset voltage, due to slightly mismatched transistors in the differential amplifier input stage, and differences in input bias currents, I^- and I^+.The output offset voltage due to mismatched bias currents I^- and I^+ can be reduced by connecting a compensating resistor, RC, in series with noninverting input. This resistor does not affect the closed-loop gain of the amplifier. The optimum value of RC is:

$$RC= R1 \parallel RF$$

When this compensating resistor is used, the magnitude of the output offset voltage due to input offset current is:

$$|V_{OS}| = (I^{+} - I^{-})\, R_F = I_{io} R_F$$

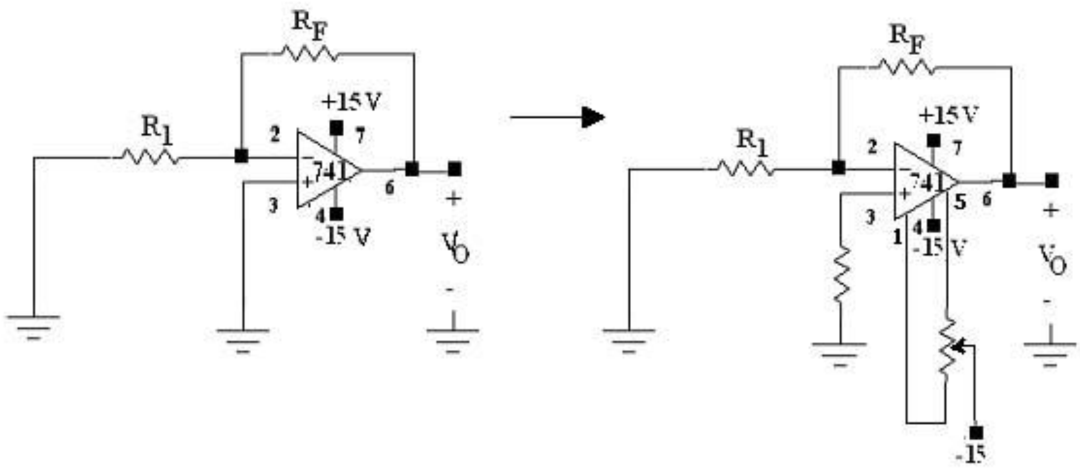
where: $|V_{OS}|$ is the magnitude of the output offset voltage

I^{-} is the input bias current at the inverting terminal

I^{+} is the input bias current at the noninverting terminal

I_{io} is the input offset current $(I^{+} - I^{-})$

Note that VOS may be either positive or negative, depending on which of I^{+} and I^{-} is larger.
The 741 op-amp has externally accessible terminals that can be used to null, or balance , the amplifier, i.e., to adjust the output offset to zero when the inputs are zero.A potentiometer is connected across pins 1 and 5 for this purpose, as shown below.
(e.g. R1= 1MΩ, RF =1MΩ, R+= 470KΩ and a 10 KΩ potentiometer) Your specific tasks are:



1. Design and construct an instrumentation amplifier using 741 operational amplifiers on a breadboard.Design the circuit for a gain of 10, and adjust for the maximum CMRR.
2. Construct a second instrumentation amplifier using the Analog Device AD620 module. Configure this circuit for a gain of 10 also.
3. For both circuits measure:a) Gain b) Common Mode Rejection Ratio (CMRR) c) Frequency responsed) Slew ratee) Noise

<u>A safety note:</u> in case, be certain that the ±15 volt supply is connected correctly to the op-amp.A few milliseconds of incorrect polarity will result in a dead module. Always check your power supply levels and polarities before connecting to the op-amp circuit!

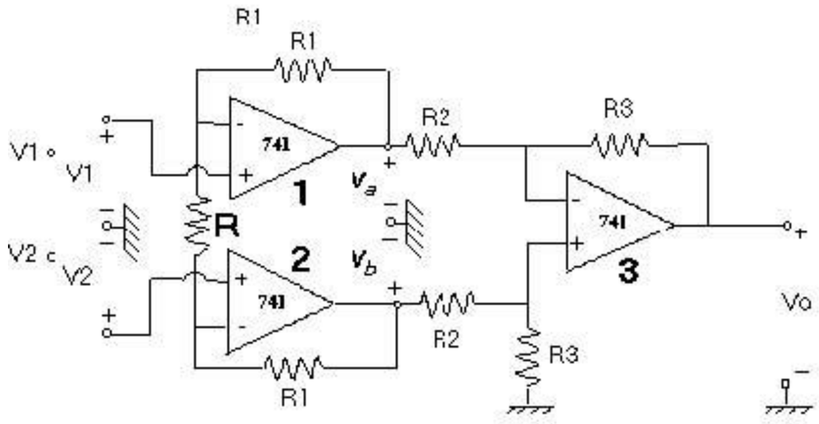


Figure 1

Experiment:

A. Designing the circuit for a gain of 10

Figure 1 above is the classic instrumentation amplifier made from 3 op-amps. If you have experience in op-amp design, feel free to design your own circuit, but for those with minimal or no design experience this is the safest bet. The most important parameter in this design is the gain
– we want you to design for a gain of 10. What resistor values do we pick to achieve this? First we need to do some basic circuit analysis.

The back end of the circuit is op-amp #3. The 2 inputs to this subcircuit are Va and Vb. Analyze this circuit in terms of Vo. Remember that the plus and minus terminals are at the same voltage, and no current flows into them. You should get Vo = (R3/R2)(Vb-Va).The front end of the circuit contains op-amps #1 and #2. We need to determine Vb and Va in terms of V1 and V2. Again noting that the plus and minus terminals on each op-amp are equal in voltage and no current flows into them, we see that the same current flows from the output terminal of 2 (at voltage Vb) thru the lower R1 resistor, then thru R, then thru the upper R1 to the output terminal of 1 (at voltage Va).Equate these currents and analyze this circuit to get an expression for Vb-Va in terms of V1 and V2. You should get Vb-Va= (V2-V1)(1+ (2R1/R)). Substituting this into the equation above, we get:

$$Vo = (V2-V1)(R3/R2)(1+(2R1/R))$$

You can control the gain by adjusting the ratio of R3 to R2, and by varying the ratio of R1 and R. As a practical matter, use resistors in the range from 10K ohms to 100K ohms.

B. Determining the Common-Mode Rejection Ratio

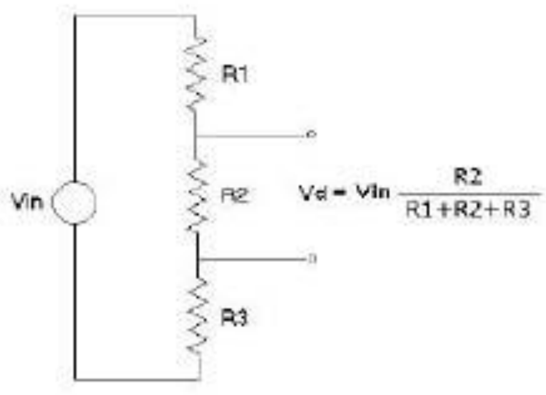
Biomedical applications of electronic circuitry tend to be in noisy locations like hospitals (noisy meaning electrical noise, though some hospitals can be just plain noisy! ☺). Also, the signals they attempt to measure, being biological, are often very small. So overhead fluorescent lights, other electronic devices, computer monitors, etc all contribute to ambient noise that can severely degrade the signal you're trying to measure. That's why instrumentation amplifiers need to have a high Common-Mode Rejection Ratio, or CMRR. A high ratio means that any noise that's on both terminals of the device (which usually comes from the environment) will tend to get cancelled out, leaving a cleaner signal to measure. This circuit will show a very high CMRR only if the resistors are accurately matched, i.e., the 2 R1s, R2s, and R3s are very close in value. Remember that standard commercial-grade resistors can vary as much as 5%, so better check several with an ohmmeter to find the two that are closest, and use them in series with low-ohm resistors to get the values even closer. We won't spend any time here rigorously defining differential and common mode voltages (if you're interested consult any current op-amp text). The results of these definitions and relationships are:

Vid = V1 – V2 (differential mode voltage)
Vic = (V1 + V2)/2 (common mode voltage)
Vo = Ad * Vid + Ac * Vic (output voltage)

that is, output is equal to the differential voltage times the differential gain (Ad), plus the common-mode voltage times the common-mode gain(Ac). The CMRR is defined as Ad/Ac, the ratios of the gains. When calculating the CMRR, always express it as a log:

CMRR = 20 log(Ad/Ac).

Measuring CMRR can be tricky. Theoretically, all you are measuring is the ratio of the differential mode (DM) gain and the common-mode (CM) gain. So you might think that you apply the same voltage to both inputs, measure the output for common-mode voltage, then apply two different voltages to both inputs to get the differential voltage, and then take the ratio. Unfortunately, since real signals are not perfect, any time you apply a real differential signal to an amplifier, you are applying both a differential and common-mode voltage. You can't separate them in real life. But the CMRR can also be defined as the ratio between the amplitude of the common mode signal (call it Vcm) and the amplitude of an equivalent differential signal (call it Vd) which would produce the same output voltage from the amplifier. So first put in a relatively large common-mode signal, i.e., Vcm = 4 or 5 volts tied to both inputs. Measure the output signal. Then put a very small differential voltage on the inputs (a voltage divider as the circuit shown below could be required), and adjust this differential voltage carefully until the output voltage just equals the output voltage of the common-mode case. That gives you your Vd. Then the CMRR = 20 log (Vd /Vcm).



C. Determining the frequency response

Frequency response just means how well the amplitude of the signal is preserved at different frequencies. The instrumentation amplifier will work well from DC (f = 0 Hz) up to many thousands of Hz, but higher than that, the signal amplitude decreases rapidly. In general, we say that the "cut-off" frequency is that frequency where the signal is just $1/\sqrt{2}$, or 0.707 of the full voltage level. Determining the frequency response in this case merely means finding the frequency where signal drops off around 70%. This is also called the 3-DB frequency. (-3 DB equals 0.707.)

D. Slew Rate

The slew rate is an indicator of how fast the circuit can change voltages. The slew rate of the circuit should be very close to the slew rate printed on the spec sheet of the op-amp, so if yours is very different (say, an order of magnitude), you're doing something wrong. To determine slew rate, put a square wave signal into the circuit, and use 2 channels of the oscilloscope to put both input and output on the same screen. Determine the total time it takes for the output to go from lower to higher voltage, and express it in the same units as you find on the spec sheet.

E. Noise

Noise is all the unwanted electronic signals coming in that you don't want to measure. This one we will leave to you: you have to determine how noisy your circuit is, and justify the method you use to measure noise. Remember from class that we characterize the noise characteristic of an amplifier by the "Noise Figure". How can you measure the noise figure of your circuit? If nobody in your group has a clue, you'll have to go and look it up in an electrical engineering text. In any case, no asking the TA or instructor! Hint: look for "RMS" and thermal noise in resistors.

Summary, REPORTing, Grading: When grading this lab, we will first check that you achieved a gain of 10, +/-5%, in your circuit. Also, we expect a CMRR of at least 40 dB for the 741 circuit. That's equivalent to getting the differences of your resistors within about 1% of each other, something you can easily achieve with the components available. We may check this during lab, but don't dismantle your circuits after you finish the lab without the TA's permission, since we may spot check them afterwards too. In the summary, include all pertinent parameters and compare and contrast the two types of op-amp. We usually expect the monolithic 620 to do better in all categories. If it doesn't, your summary should include possible reasons for the anomalies.

!!! Please write your summary clear, don't forget to add your ID# and name. You are free for the written language !!!