Lab 2 – Operational Amplifiers: Part I

Objectives

- To execute the instructions of Lab 2 as provided for ECE 3410 from Canvas (https://usu.instructure.com/).
  - To demonstrate the principle of superposition by examining the characteristics of a weighted summer op amp configuration.
  - To observe the effects of non-ideal amplifier characteristics, including finite input resistance, finite open-loop gain, and systematic offset voltages.
  - To demonstrate methods of offset cancellation via capacitive coupling.

Preparation

Component and Materials

- 741 operational amplifiers (2)
- 10nF capacitor (1)
- 10kΩ resistors (5)
- 10kΩ potentiometer (1)
- Breadboard and Hookup Wire

Equipment

- Banana Cable Sets (4)
- Oscilloscope Probes (2)
- Potentiometer Adjustment Tool (1)
- BNC-to-BNC Cable (1)
- BNC-to-Alligator Cable (1)

Pre-Lab Analysis

➤Analytical

Exercise 1

$$\Rightarrow_1^{SP} \quad v_2 = 0\text{ V} \quad \Rightarrow_2^{\therefore} \quad v_{out_1} = -\frac{R_F}{R_1} v_1$$

$$\Rightarrow_3^{SP} \quad v_1 = 0\text{ V} \quad \Rightarrow_4^{\therefore} \quad v_{out_2} = -\frac{R_F}{R_2} v_2$$

$$\Rightarrow_5^{\Sigma} \quad v_{out} = v_{out_1} + v_{out_2} = -\frac{R_F}{R_1} v_1 - \frac{R_F}{R_2} v_2$$

$$\Rightarrow_6 \quad v_{out} = -v_1 - 2v_2 \quad \Rightarrow_7^{\therefore} \quad \frac{R_F}{R_1} = 1 \quad \frac{R_F}{R_2} = 2$$

$$\Rightarrow_8 \quad R_F = 10\text{ k}\Omega$$

$$\Rightarrow_9^{\therefore} \quad R_1 = 10\text{ k}\Omega \quad R_2 = 5\text{ k}\Omega = 10\text{ k}\Omega \,||\, 10\text{ k}\Omega$$

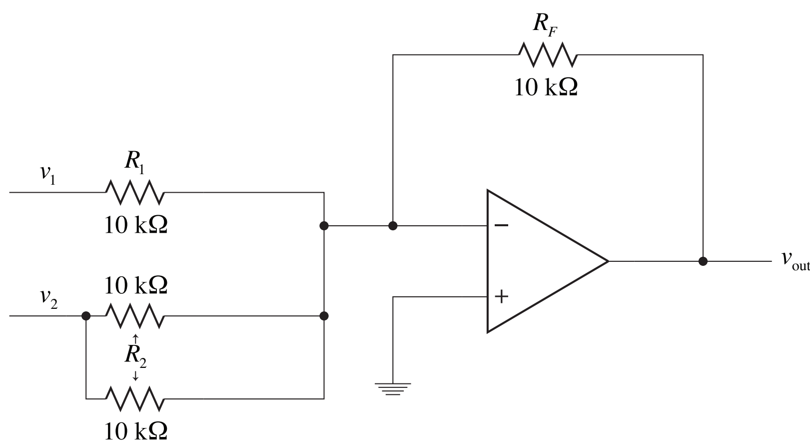

Figure 1: Circuit for Exercise 1.

Exercise 2

$\Rightarrow_1 \quad R_F = 10\ \text{k}\Omega \quad R_1 = 10\ \text{k}\Omega \quad R_2 = 5\ \text{k}\Omega = 10\ \text{k}\Omega \,\|\, 10\ \text{k}\Omega \quad C = 10\ \text{nF}$

$$\Rightarrow_2^{\text{NVA}} \quad \frac{v_\text{N} - v_\text{out}}{R_F} + \frac{v_\text{N} - v_1}{R_1} + \frac{v_\text{N} - v_2}{R_2 + \frac{1}{sC}} = 0 \quad v_\text{N} = v_\text{P} = 0\ \text{V}$$

$$\Rightarrow_3^{\text{SP}} \quad v_2 = 0\ \text{V} \quad \Rightarrow_4^{\therefore} \quad v_{\text{out}_1} = -\frac{R_F}{R_1} v_1$$

$$\Rightarrow_5 \quad H_1(s) = \frac{v_{\text{out}_1}}{v_1} \quad \Rightarrow_6^{\therefore} \quad H_1(s) = -\frac{R_F}{R_1}$$

$$\Rightarrow_7^{\text{SP}} \quad v_1 = 0\ \text{V} \quad \Rightarrow_8^{\therefore} \quad v_{\text{out}_2} = -\frac{R_F C s}{R_2 C s + 1} v_2$$

$$\Rightarrow_9 \quad H_2(s) = \frac{v_{\text{out}_2}}{v_2} \quad \Rightarrow_{10}^{\therefore} \quad H_2(s) = -\frac{R_F C s}{R_2 C s + 1}$$

$$\Rightarrow_{11}^{\Sigma} \quad H(s) = H_1(s) + H_2(s) \quad \Rightarrow_{12}^{\therefore} \quad H(s) = -\frac{R_F}{R_1} - \frac{R_F C s}{R_2 C s + 1}$$

$$\Rightarrow_{13} \quad \omega_c = \frac{1}{R_2 C} \quad \Rightarrow_{14} \quad f_c = \frac{1}{2\pi R_2 C} \quad \Rightarrow_{15}^{\therefore} \quad \boxed{f_c = 3.18\ \text{kHz}}$$

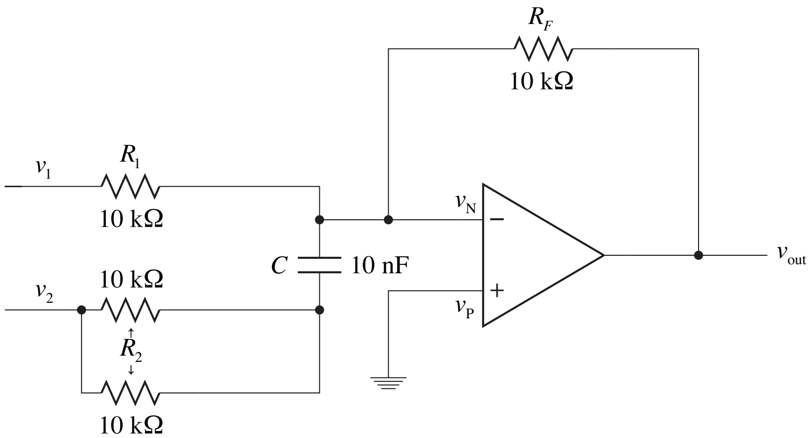

Figure 2: Circuit for Exercise 2.

Exercise 3

$\Rightarrow_1 \quad R_F = 10\ \text{k}\Omega \quad R_1 = 10\ \text{k}\Omega \quad R_2 = 5\ \text{k}\Omega = 10\ \text{k}\Omega \,\|\, 10\ \text{k}\Omega \quad C = 10\ \text{nF} \quad R_X = 10\ \text{k}\Omega$

$$\Rightarrow_2^{\text{NVA}} \quad \frac{v_{\text{N}_1} - v_\text{out}}{R_F} + \frac{v_{\text{N}_1} - v_1}{R_1} + \frac{v_{\text{N}_1} - v_{\text{N}_2}}{R_2} = 0$$

$$\frac{v_{\text{P}_2} - v_2}{\frac{1}{sC}} + \frac{v_{\text{P}_2}}{R_X} = 0 \quad v_{\text{N}_1} = v_{\text{P}_1} = 0\ \text{V} \quad v_{\text{N}_2} = v_{\text{P}_2}$$

$$\Rightarrow_3^{\text{SP}} \quad v_2 = 0\ \text{V} \quad \Rightarrow_4^{\therefore} \quad v_{\text{out}_1} = -\frac{R_F}{R_1} v_1$$

$$\Rightarrow_5 \quad H_1(s) = \frac{v_{\text{out}_1}}{v_1} \quad \Rightarrow_6^{\therefore} \quad H_1(s) = -\frac{R_F}{R_1}$$

$$\Rightarrow_7^{\text{SP}} \quad v_1 = 0\ \text{V} \quad \Rightarrow_8^{\therefore} \quad v_{\text{out}_2} = -\frac{R_F R_X C s}{R_2 (R_X C s + 1)} v_2$$

$$\Rightarrow_9 \quad H_2(s) = \frac{v_{\text{out}_2}}{v_2} \quad \Rightarrow_{10}^{\therefore} \quad H_2(s) = -\frac{R_F R_X C s}{R_2 (R_X C s + 1)}$$

$$\Rightarrow_{11}^{\Sigma} \quad H(s) = H_1(s) + H_2(s) \quad \Rightarrow_{12}^{\therefore} \quad H(s) = -\frac{R_F}{R_1} - \frac{R_F R_X C s}{R_2 (R_X C s + 1)}$$

$$\Rightarrow_{13} \quad \omega_c = \frac{1}{R_X C} \quad \Rightarrow_{14} \quad f_c = \frac{1}{2\pi R_X C} \quad \Rightarrow_{15}^{\therefore} \quad \boxed{f_c = 1.59\ \text{kHz}}$$

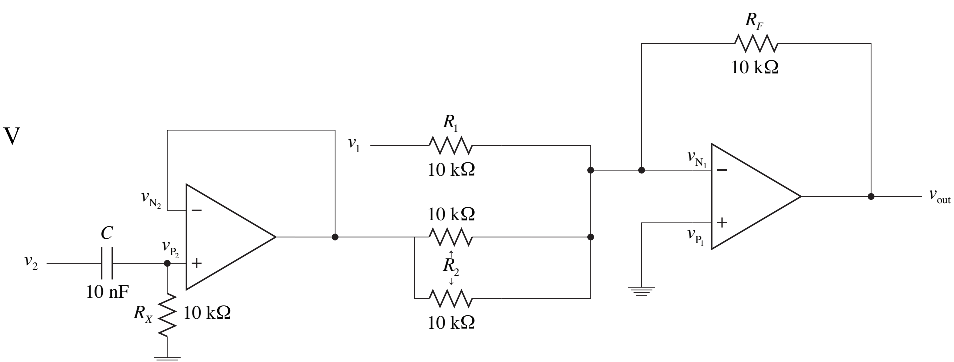

Figure 3: Circuit for Exercise 3.

➤Calculated

exercise1.sp (Procedure 1) >>

```
Lab 2, Exercise 1, ECE 3410
***************************
* By Chris Winstead
***************************

* Include the model file:
.include lab_parts.md

* Power supplies:
VDD ndd 0 DC 15V
VSS nss 0 DC -15V

* The input voltage sources
V1 n1 0 DC 1V
V2 n2 0 DC 5V

* Resistors
R1 n1 nn 10k
R2 n2 nn 5k
RF nn nout 10k

* Op Amp Model
X1 0 nn ndd nss nout uA741

* Control Commands:
.control
op
print all

echo "Result for Part A:"
print v(nout)

alter V2 DC 0V

dc V1 1V 2V 0.05V
plot v(nout)

echo "Results for Part B:"

* Print out specific data points:
meas dc vo1 FIND v(nout) AT=1
meas dc vo2 FIND v(nout) AT==1.25
meas dc vo3 FIND v(nout) AT==1.5
meas dc vo4 FIND v(nout) AT==1.75
meas dc vo5 FIND v(nout) AT==2.0

let gain='(vo5 - vo1)/(2.0-1.0)'
echo The measured gain is $&gain

.endc
.end
```

exercise2.sp (Procedure 2) >>

```
Lab 2, Exercise 2, ECE 3410
***************************
* By Chris Winstead
***************************

* Include the model file:
.include lab_parts.md

*===== CIRCUIT DESCRIPTION ======
* Power supplies:
VDD ndd 0 DC 15V
VSS nss 0 DC -15V

* The input voltage sources
V1 n1 0 DC 1V
V2 n2 0 DC 0V AC 1 SIN(0V 0.5V 50kHz)

* Resistors
R1 n1 nn 10k
R2 n3 nn 10k
RF nn nout 10k
C1 n2 n3 10n

* Op Amp Model
X1 0 nn ndd nss nout uA741

*================================
* CONTROL COMMANDS:
*================================
.control

* Declare some variables to store
results in:
let ofs_1=unitvec(6)
let ofs_2=unitvec(6)
let ofs_out=unitvec(6)
let idx=0

* Automate a batch of simulations:

*----- START OF LOOP ----*
foreach vo1 1 2
foreach vo2 0.5 1.0 1.5

* Alter V1 and V2:
alter V1 DC $vo1
alter @V2[sin] = [ $vo2 0.5 50k ]
* ^^^Quirk: make sure to put spaces
around
* the brackets in the alter statement

* Do a transient simulation
tran 1u 100u
plot v(n2) v(nout)

* Measure the output offset:
meas tran ofs1 AVG v(nout)

* Record results from this simulation:
let ofs_1[idx]=$vo1
let ofs_2[idx]=$vo2
let ofs_out[idx]=ofs1
```

exercise3.sp (Procedure 3) >>

```
Lab 2, Exercise 3, ECE 3410
***************************
* By Chris Winstead
* Modified by Joel Meine
***************************

* Include the model file:
.include lab_parts.md

*===== CIRCUIT DESCRIPTION ======
* Power supplies:
VDD ndd 0 DC 15V
VSS nss 0 DC -15V

* The input voltage sources
V1 n1 0 DC 1V
V2 n2 0 DC 0V AC 1 SIN(0V 0.5V 50kHz)

* Resistors
R1 n1 nn1 10k
R2 nout2 nn1 5k
RF nn1 nout1 10k
C1 n2 pp2 10n
RX 0 pp2 10k
R0 nn2 nout2 0

* Op Amp Model
X1 0 nn1 ndd nss nout1 uA741
X2 pp2 nn2 ndd nss nout2 uA741

*================================
* CONTROL COMMANDS:
*================================
.control

*----- START OF LOOP ----*
foreach rff 10k 20k 40k

* Alter RF:
alter RF $rff
* ^^^Quirk: make sure to put spaces
around
* the brackets in the alter statement

*----- AC SIMULATION -----*
ac dec 10 100 1e6

plot vdb(nout)-vdb(n2)

meas ac Av0  FIND vdb(nout) AT=10k
let A3dB=Av0-3
print A3dB

meas ac fhigh WHEN vdb(nout)=$&A3dB
FALL=LAST
meas ac flow  WHEN vdb(nout)=$&A3dB
RISE=1
meas ac ft    WHEN vdb(nout)=0

end
*----- END OF LOOP ----*
.endc
.end
```

```
* Increment the loop index:
let idx=idx+1
end
end
*----- END OF LOOP ----*

*----- AC SIMULATION -----*
ac dec 100 1 1e6

plot vdb(nout)-vdb(n2)

meas ac Av0  FIND vdb(nout) AT=10k
let A3dB=Av0-3
print A3dB

meas ac fhigh WHEN vdb(nout)=$&A3dB
FALL=LAST
meas ac flow  WHEN vdb(nout)=$&A3dB
RISE=1
meas ac ft    WHEN vdb(nout)=0

* Print out the reults:
print ofs_1 ofs_2 ofs_out

.endc
.end
```

log.txt >>

Procedure 1

```
Result for Part A:
v(nout) = -10.9989

Results for Part B:
vo1 = -0.999105
vo2 = -1.249100
vo3 = -1.499095
vo4 = -1.749090
vo5 = -1.999085
The measured gain is -0.99998
```

Procedure 2

```
------------------------------------------------------
Index   ofs_1           ofs_2           ofs_out
------------------------------------------------------
0       1.0             0.5             -1.00469
1       1.0             1.0             -1.00469
2       1.0             1.5             -1.00469
3       2.0             0.5             -2.01294
4       2.0             1.0             -2.01294
5       2.0             1.5             -2.01294
```

Procedure 3

```
RF | Mid-Band Gain (av0) | Cutoff Frequency, Upper (fhigh) | Unity-Gain Frequency (ft)

10k | 5.91 dB | 296.98 kHz | 927.17 Hz
20k | 11.91 dB | 158.91 kHz | 412.54 Hz
40k | 17.86 dB | 83.06 kHz | 200.67 Hz

· As the RF value is increased...
➤ the mid-band gain increases,
➤ the upper cutoff frequency decreases,
➤ and the unity gain frequency decreases.

The magnitude response plot for each case shows that the response reliably holds it's essential form as a bandpass
filter. As the value of the feedback resister is increased, however, the trend of the plots shows that the bandwidth
of the bandpass filter decreases while the mid-band gain increases.
```

Lab Experiments

Procedure 1

Step A >>

Voltage, Measured (v_1) =	1.00 V
Voltage, Measured (v_2) =	5.00 V
Voltage, Meausred (v_{out}) =	-10.92 V (0.7% err.)

Step B >>

v_2 = 0 V

Measured (v_1)	Measured (v_{out})
1.00 V	-1.00 V (0.0% err.)
1.25 V	-1.24 V (0.8% err.)
1.51 V	-1.50 V (0.0% err.)
1.75 V	-1.74 V (0.6% err.)
2.00 V	-1.99 V (0.5% err.)

Procedure 2

Step A.ii >>

	v_2	v_{out}
Peak-to-Peak, Measured =	1.01 V	1.80 V
Offset Voltage, Measured =	-10.8 mV	-1.00 V

Step A.iv >>

- It is observed that v_{out} will filter out the DC of v_2 due to the capacitor.

Step A.iii >>

$$K(\text{gain}) = \frac{\omega}{\sqrt{\omega^2 + \omega_c^2}} \qquad \begin{aligned} \omega &= 2\pi f \\ f &= 50 \text{ kHz} \\ \omega_c &= 20 \text{ krad/s} \end{aligned}$$

$$\Rightarrow \quad K(\text{gain}) = 0.998 \text{ V/V}$$

- With the potentiometer adjusted so that v_1 = 1 V as from Procedure 1 which yields a gain value of 1 V/V for v_1, it is observed that the frequency dependent gain is nearly equal to the DC gain from Procedure 1.

Step A.v >>

$v_2 = 0.5\sin(2\pi 50_k)$

Measured (v_1)	Measured (v_{out})
0.50 V	-0.48 V (4.0% err.)
1.00 V	-0.99 V (1.0% err.)
1.50 V	-1.51 V (0.7% err.)

Step B >>

Cutoff Frequency, Low = (3.18 kHz)	25 kHz (686% err.)
Cutoff Frequency, High = (593.96 kHz)	265 kHz (55% err.)

Procedure 3

Cutoff Frequency, Low = (1.59 kHz)	15 kHz (843% err.)
Cutoff Frequency, High = (269.98 kHz)	220 kHz (18.5% err.)

Commentary

- Improved familiarization and increased experience with the use of the principle of superposition (SP) via circuit analysis methods of operational amplifiers using ideal op-amp laws.
- As the pre-lab analysis metrics derived from the analytical and calculated results were not the same, the results between the analytical and calculated results can not readily be compared to observe consistency. Thus yielding no readily sensible conclusion as far as the cutoff frequencies are concerned. The voltage results, however, did yield sensible consistency.

- After conducting the lab experiments, the measured values and calculated values in procedures 1 and 2 when observing v_{out} in relation to v_1 did yield expected results with exceedingly marginal error. As the percentage of error yielded no systematic offset, therefore the op amp exhibited random voltage offset.
- The cutoff frequency analysis, however, yielded no sensibly consistent results between the measured and calculated values. As the circuit analyzed in each procedure was only a modified version of a high-pass filter, despite the lab procedure description, all previously acquired knowledge contradicts the notion of a high-pass filter having a low and high cutoff frequency. That concept is reserved to band-pass and band-reject filters only. A comparison of the measured and calculated cutoff frequencies yielded exceeding degrees of error to which no readily sensible conclusion can be derived. User error during the lab experiment procedure for deriving the cutoff frequencies is the likely source for the lack of positive correlation against the calculated results of the pre-lab analysis.