CE2004: Circuits & Signal Analysis - Lab Report (Lab 3)

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1. Abstract

In Lab 3, we are asked to investigate the characteristics of linear op-amps circuits through their operation in some common applications, namely potentiometer, unity gain buffer, non-inverting amplifier, inverting amplifier and summing amplifier.

In this experiment, the standard industrial op-amp "741" is used in various circuit configurations to form the application discussed above. Figure 1 shows the pin-out diagram for the 741 op-amp that is referred to make connection for the circuits in experiments 2.1 and 2.2.

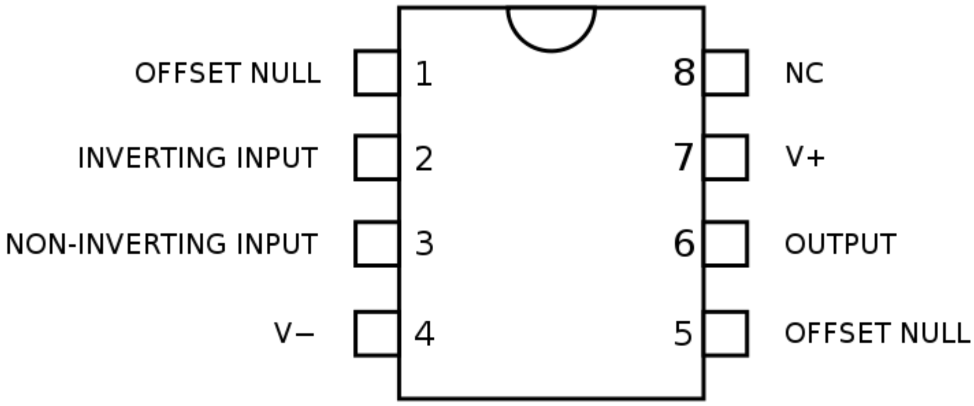

Figure 1. Pin-out diagram for "741" Op-amp

2. Experiments

2.1. Inverting Amplifier

a. Circuit Configuration with DC Power Supply as Input

The set up for Inverting Amplifier circuit with DC Power Supply is shown below in figure 2, where R_F = 33kΩ or 68kΩ based on the lab manual.

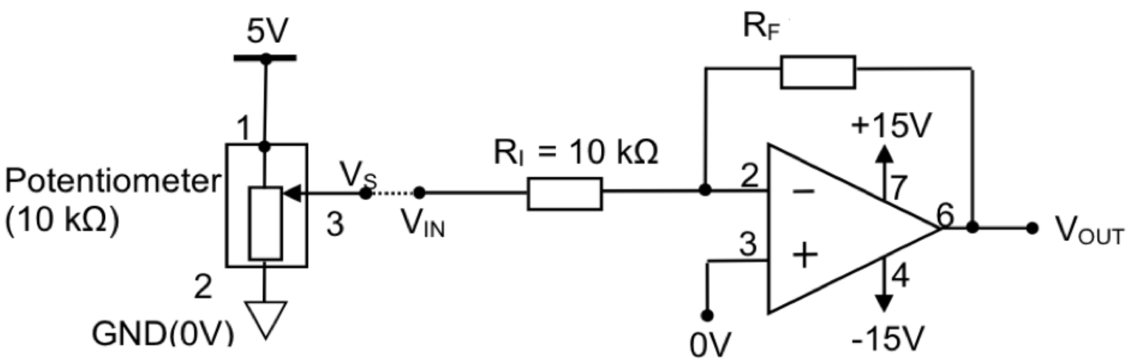

Figure 2. Inverting Amplifier Set-up (with DC Input, R_F = 33kΩ or 68kΩ

For inverting amplifiers, the gain of the amplifier A_0 can be theoretically calculated as following (based on the set-up in figure 2):

$$A_0 = -\frac{R_f}{R_1} \qquad (1)$$

From this calculated gain, V_{out} can be calculated by the formula:

$$V_{out} = A_0 * V_{in} \qquad (2)$$

Task 1: Measure V_{out}, V_{in} for values of V_{in} from 0V to 5V in 1V intervals. Plot V_{out} against V_{in} to derive the voltage gain of inverting amplifier.

We turn the potentiometer (knob) around to vary the V_{in} value. Using a Digital Multimeter to measure V_{out} and V_{in} at V_{in} = 0V, 1V, 2V, 3V, 4V, 5V.

When R_f = 33kΩ,

- From (1), **calculate voltage gain of the inverting op-amp = -33/10 = -3.3**
- From (2), V_{out} = -3.3 * V_{in}. If after calculation V_{out} > 15V, V_{out} = 15V and if V_{out} <-15V, V_{out} = -15V (**theoretical saturation voltage is cap at +15V and -15V due to constraint of power supply**)
- The result of measurement for V_{out} at different interval of V_{in} as well as the corresponding calculated V_{out} is shown in table 1.

V_{in}	V_{out}(measured)	V_{out}(calculated)	Difference (absolute value)
0.000 V	0.002 V	0.000 V	0.002 V
1.001 V	-3.330 V	-3.303 V	0.027 V
2.000 V	-6.660 V	-6.600 V	0.060 V
3.002 V	-9.993 V	-9.907 V	0.086 V
4.000 V	-12.908 V	-13.200 V	0.292 V
5.004 V	- 12.921 V	-15.000 V	2.079 V

Table 1. V_{out} measured vs theoretically calculated when R_f = 3.3kΩ

- Based on the V_{out} measured at the 6 intervals of V_{in}, we plot V_{out} against V_{in} and obtain a graph as shown in figure 3. Ignore the saturated portion of the graph for a best fit line to analyse actual voltage gain of the amplifier.
- From figure 3, take two points **(0.50, -1.64)** and **(2.50, -8.40)** which is in range where the op-amp output is not saturated yet. The gradient of the plot in this unsaturated range is $\frac{-8.40-(-1.64)}{2.50-0.50} = -3.38$. Thus, **actual voltage gain of this inverting amplifier configuration = -3.38.**

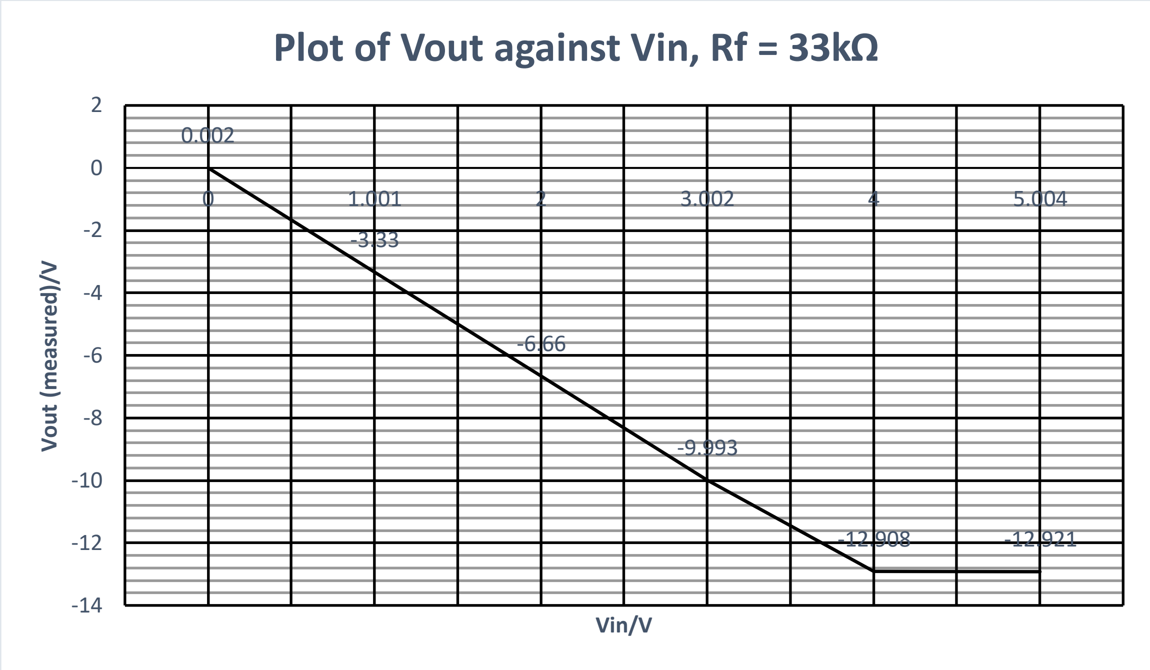

Figure 3. Plot of V_{out} vs V_{in} when R_f = 33kΩ

When R_f = 68kΩ,

- From (1), **calculate voltage gain of the inverting op-amp = -68/10 = -3.3**
- From (2), V_{out} = -6.8 * V_{in}. If after calculation V_{out} > 15V, V_{out} = 15V and if V_{out} <-15V, V_{out} = -15V (as **theoretical saturation voltage is cap at +15V and -15V due to constraint of power supply**)
- The result of measurement for V_{out} at different interval of V_{in} as well as the corresponding calculated V_{out} is shown in table 2.

V_{in}	V_{out}(measured)	V_{out}(calculated)	Difference (absolute value)
0.000 V	0.002 V	0.000 V	0.002 V
1.002 V	-6.918 V	-6.815 V	0.103 V
2.004 V	-12.926 V	-13.627 V	0.701 V
3.003 V	-12.936 V	-15.000 V	2.064 V
4.000 V	-12.936 V	-15.000 V	2.064 V
5.002 V	- 12.936 V	-15.000 V	2.064 V

Table 2. V_{out} measured vs theoretically calculated when R_f = 6.8kΩ

- Based on the V_{out} measured at the 6 intervals of V_{in}, we plot V_{out} against V_{in} and obtain a graph as shown in figure 4. Ignore the saturated portion of the graph for a best fit line to analyse actual voltage gain of the amplifier.
- From figure 4, take two points **(0.50, -3.4)** and **(2.50, -9.96)** which is in range where the op-amp output is not saturated yet. The gradient of the plot in this unsaturated range is $\frac{-10.0-(-3.4)}{2.50-0.50} = -6.70$. **Thus, actual voltage gain of this inverting amplifier configuration = -6.70.**

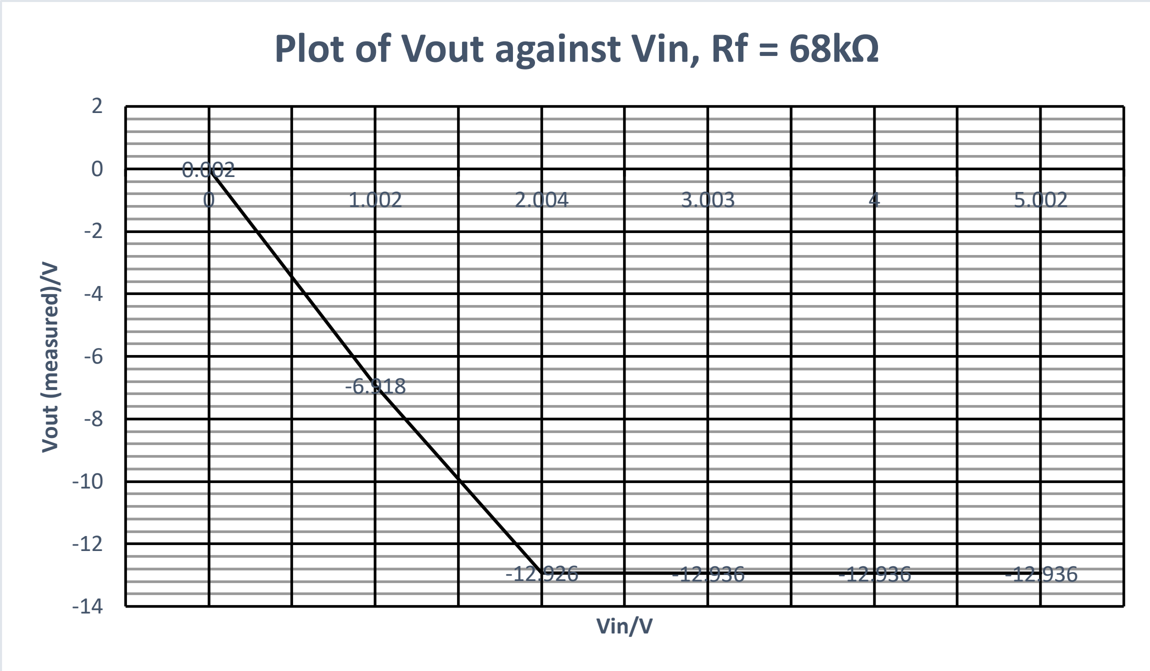

Figure 4. Plot of Vout vs Vin when Rf = 68kΩ

Observation:

- Actual voltage gains of both inverting amplifiers are **relatively close and consistent** with the theoretically predicted value and has **very high precision** (< 5.00% of error).
  - ✓ R_f = 33kΩ : actual gain = -3.38 vs calculated gain = -3.3. Percentage error = $\frac{-3.38-(-3.3)}{-3.3} * 100\% = 2.42\%$
  - ✓ R_f = 68kΩ : actual gain = -6.70 vs calculated gain = -6.8. Percentage error = $\frac{-6.7-(-6.8)}{-6.8} * 100\% = 1.47\%$
- The **voltage gains of both inverting amplifiers are negative**, the output voltages' polarity is in 180^o phase difference with their input voltages. This is as expected from the theoretical derived voltage gains since we are using the inverting amplifiers in this task, which is known to produce an amplified output value with opposite polarity with input.
- The **saturated voltage for experimental op-amp is clipped at -12.936V** and is lower than the predicted clipped -15V by theory and based on the power supply given. This is because real, practical 741 op amps are non-ideal and is known to have output range of about 2V under the theoretical range (which is what observed in this case as |-15+12.936| = 2.064V
- The **inverting amplifiers in our experiment behaves linearly** like expected (in non-saturated range). This is shown by the change in gradient between R_f =33k and 68kΩ, where the later configuration result in a steeper gradient or decreases in V_{out} for the same V_{in} as the former. Thus a greater gain

magnitude produces a larger magnitude of change in V_{out} for the same interval of V_{in} like what being known for op-amps.

Task 2: Set V_S to 2V. Disconnect the potentiometer output V_S from the amplifier V_{IN} and measure V_S again. Note any difference between the values measured.

Refer to figure 2, we adjust the knob of potentiometer and measure the V_{in} value with multimeter such that it is = 2V (like the procedure to obtain V_{out} for corresponding interval of V_{in}).

- **V_S obtained when V_{in} = 2.000V is 2.5423V** instead of 2.000V as expected. For this inverting amplifier, the potential at inverting terminal is taken as a virtual ground (V- = 0) and is equal to V+ terminal value where it is connected to ground. In this configuration, the input impedance of amplifier is determined by R_1.
- Since $R_1 = 10k\Omega$ and is finite, there is current flowing into the V- terminal = $(V_s - V\text{-})/R_1 = (2.5423 - 0)/10k = 2.5423$ mA. Therefore, **the input impedance is not ideal (infinite)** in this inverting op-amp as $Z_{in} = R_1 = V_s/I$ = 2.5423/2.5423m = $10k\Omega$. As the input impedance is finite, **there is current flowing from the power supply (potentiometer where V_s).** Thus, the actual V_{in} received by amplifier is less than V_S (2.000V < 2.5423V) due to the input impedance value, which induce a small current flowing into the V- terminal and **lead to voltage drop across R_1**, explained the mis-match of V_s value.

b. Circuit Configuration with Sinusoidal Signal as Input

Task 3: Set $R_F = 33K\Omega$. Connect V_{IN} to the output of a function generator. Connect the -ve terminal of the function generator to GND of the power supply (not to -15V). Set the function generator to supply a 1KHz sine wave of $3V_{PK\text{-}PK}$ amplitude. Observe the waveforms at V_{IN} and V_{OUT} on the oscilloscope and sketch the waveforms.

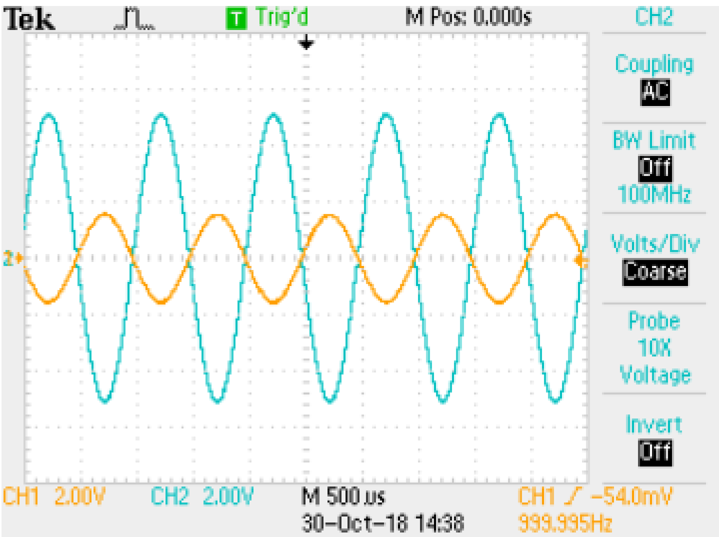

Figure 5. Waveform of V_{out} (blue) vs V_{in} (yellow) for inverting amplifier with R_f=33kΩ

Following the procedure described above, make the change to figure 2 circuit configuration. We can obtain the waveform as shown in figure 5 from oscilloscope.

- **V_{out} waveform obtained is a complete sinusoidal waveform**. This shown that there were no clipping phenomenon happens and the V_{out} due to V_{in} waveform was not at saturated value at all. This is as expected as the experimental gain was determined to be -3.38 for this amplifier and V_{in} = 3V (Peak-Peak from -1.5V to 1.5V, offset = 0). Thus the max V_{out} = 5.07V and min V_{out} = -5.07V, which is way lower than the saturated value of 12.936V and -12.936V determined above.
- Polarity wise, **the V_{out} waveform is 180^o out of phase with the V_{in} waveform.** This is the expected behaviour for an inverting amplifier with a negative gain.
- Amplitude wise, the **V_{out} waveform's amplitude is 3.38 times the V_{in} amplitude** (consistently throughout the waveform). This is because the gain of this amplifier configuration has magnitude > 1 so the amplitude change should be more than unity, equal to the magnitude of voltage gain = |-3.38| = 3.38 as determined.
- **The waveform of input and output is continuous and V_{out} change linearly with V_{in} value**, shown by the corresponding sinusoidal waveform correspond to that of V_{in}.

2.2. Non-Inverting Amplifier

a. Circuit Configuration with DC Power Supply as Input

The set up for Non-Inverting Amplifier circuit with DC Power Supply is shown below in figure 6 based on the lab manual.

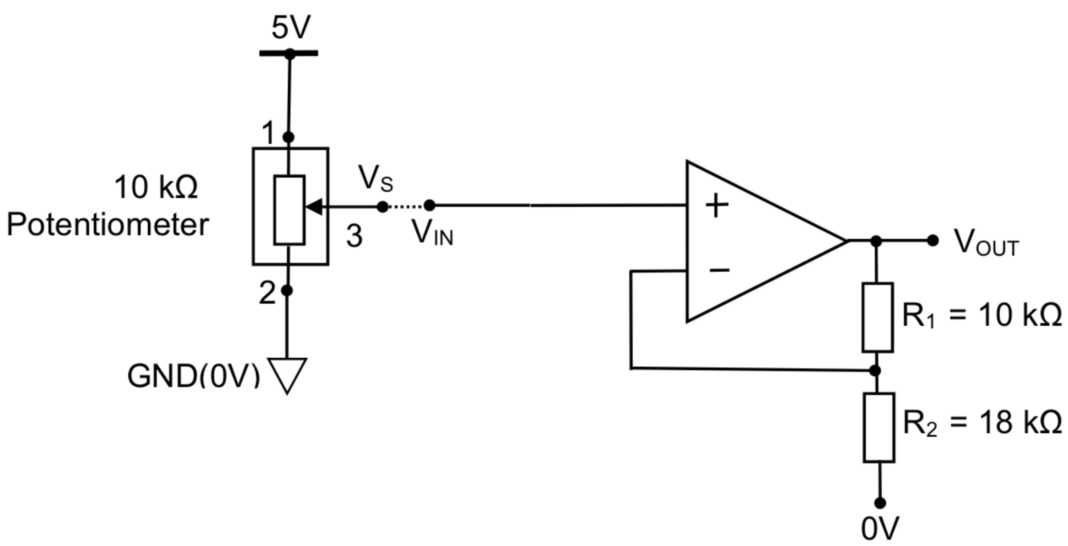

Figure 6. Non-Inverting Amplifier Set-up (with DC Input)

For non-inverting amplifiers, the gain of the amplifier A_0 can be theoretically calculated as following (based on the set-up in figure 2):

$$A_0 = 1 + \frac{R_1}{R_2} \qquad (3)$$

From this calculated gain, V_{out} can be calculated by the formula:

$$V_{out} = A_0 * V_{in} \quad (4)$$

Task 1: Measure V_{out}, V_{in} for values of V_{in} from 0V to 5V in 1V intervals. Plot V_{out} against V_{in} to derive the voltage gain of non-inverting amplifier.

We turn the potentiometer (knob) around to vary the V_{in} value. Using a Digital Multimeter to measure V_{out} and V_{in} at V_{in} = 0V, 1V, 2V, 3V, 4V, 5V.

- From (3), **calculate voltage gain of the non-inverting op-amp = 1 + (10/18) = 1.56**
- From (4), V_{out} = 1.556 * V_{in}. If after calculation V_{out} > 15V, V_{out} = 15V and if V_{out} <-15V, V_{out} = -15V (**theoretical saturation voltage is cap at +15V and -15V due to constraint of power supply**)
- The result of measurement for V_{out} at different interval of V_{in} as well as the corresponding calculated V_{out} is shown in table 3.

V_{in}	V_{out}(measured)	V_{out}(calculated)	Difference (absolute value)
0.000 V	0.001 V	0.000 V	0.001 V
1.000 V	1.555 V	1.556 V	0.001 V
2.002 V	3.112 V	3.115 V	0.003 V
3.001 V	4.664 V	4.670 V	0.006 V
4.000 V	6.215 V	6.224 V	0.009 V
5.000 V	7.768 V	7.780 V	0.012 V

Table 3. V_{out} measured vs theoretically calculated for non-inverting amplifier

- Based on the V_{out} measured at the 6 intervals of V_{in}, we plot V_{out} against V_{in} and obtain a graph as shown in figure 7. This is also the best fit line.
- From figure 7, take two points **(0.50, 0.80)** and **(4.50, 7.00)** which is in range where the op-amp output is not saturated yet. The gradient of the plot in this unsaturated range is $\frac{7.00-0.80}{4.50-0.50} = 1.55$. **Thus, actual voltage gain of this non-inverting amplifier configuration = 1.55.**

Observations:

- **Actual voltage gain of non-inverting amplifier is relatively close and consistent** with the theoretically predicted value and has very **high precision** (< 5.00% of error). Actual gain = 1.55 vs calculated gain = 1.556. Percentage error = $\frac{1.556-1.55}{1.556} * 100\% = 0.39\%$

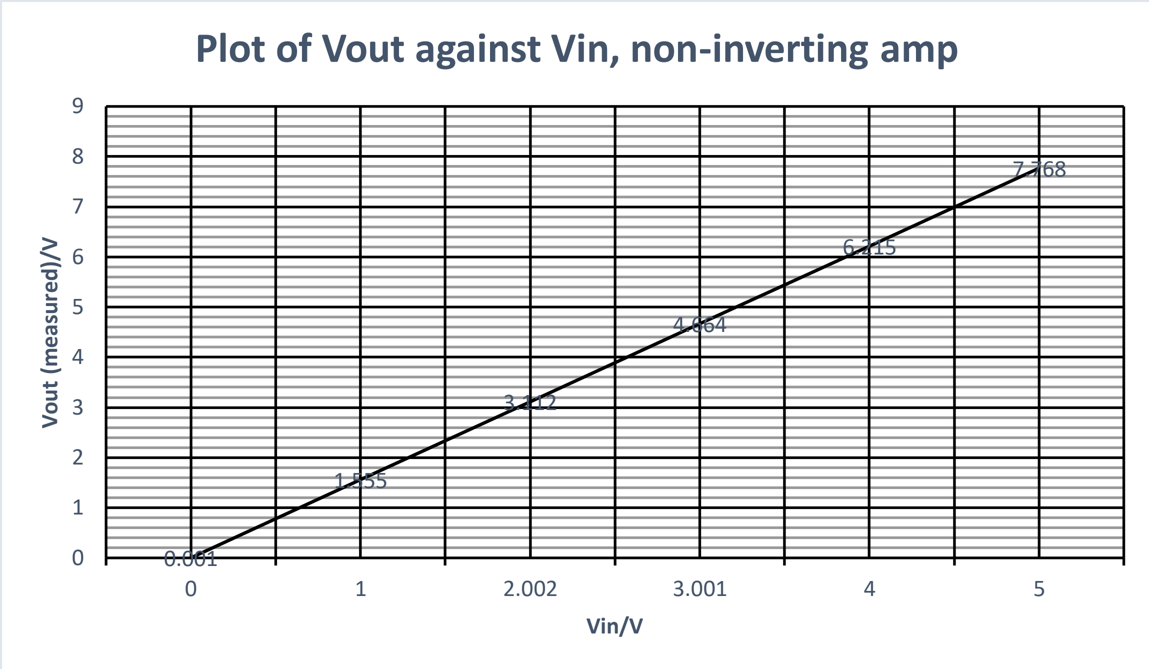

Figure 7. Plot of Vout against Vin, non-inverting amp

- The **voltage gain of non-inverting amplifier is non-negative**, the output voltages' polarity is in phase with input voltages. This is as expected from the theoretical derived voltage gain since we are using the non-inverting amplifier in this task, which is known to produce an amplified output value with no change in polarity compared to input.
- **No saturation range in output** as max V_{out} recorded = 7.768V and is way lower than the saturated voltage level determined in part 2.1.a
- **The non-inverting amplifiers in our experiment behaves linearly** like expected . At every input interval, the output voltage is amplified by a gain factor of 1.55 as determined above. The gradient of the plot is a nice linear model, with very big linear region (no sharp swing of value of output voltage from 0 to saturated value).

Task 2: Set V_S to 2V. Disconnect the potentiometer output V_S from the amplifier V_{IN} and measure V_S again. Note any difference between the values measured.

Refer to figure 6, we adjust the knob of potentiometer and measure the V_{in} value with multimeter such that it is = 2V (similar to the procedure to obtain V_{out} for corresponding interval of V_{in}).

- **V_S obtained when V_{in} = 2.000V is 2.000V** as expected. For this non-inverting amplifier, the potential at both inverting and non-inverting terminal is assumed to be equal.
- Unlike in 2.1.a, where the amplifier has R_1 = 10kΩ, this non-inverting amplifier do not have this input resistor. Thus, the input impedance can be assumed to be infinite and as a result, no current flow into the non-inverting terminal. Therefore, **there is no current flowing from the power supply (potentiometer where V_s) into V+ (non-inverting terminal).** Thus, the actual

V_{in} is equal to V_S. Due to the input impedance value = infinite, **no voltage drops between V_S into V+ terminal**, explained the expected of V_s value to be the same with or without connecting to the amplifier.

b. Circuit Configuration with Sinusoidal Signal as Input

Task 3: Connect V_{IN} to the output of a function generator. Connect the -ve terminal of the function generator to GND of the power supply (not to -15V). Set the function generator to supply a 1KHz sine wave of $3V_{PK-PK}$ amplitude. Observe the waveforms at V_{IN} and V_{OUT} on the oscilloscope and sketch the waveforms.

Following the procedure described above, make the change to figure 6 circuit configuration. We can obtain the waveform as shown in figure 8 from oscilloscope.

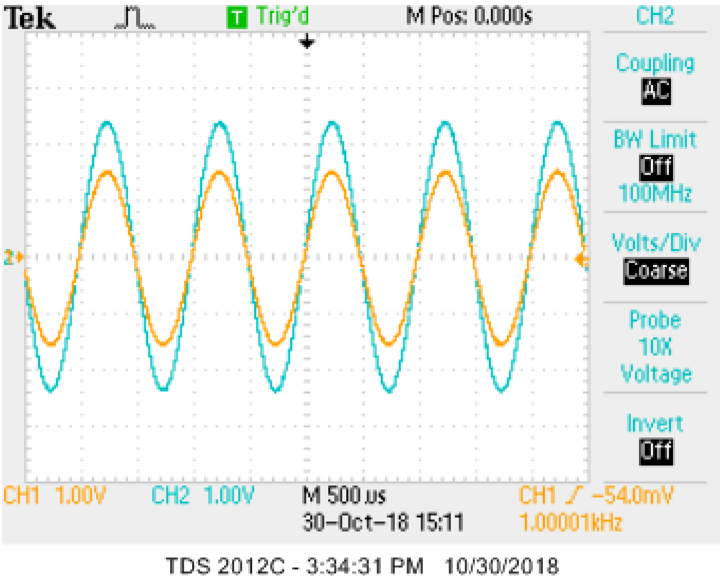

Figure 8 Waveform of Vout (blue) vs Vin (yellow) for non-inverting amplifier

- **V_{out} waveform obtained is a complete sinusoidal waveform**. This shown that there were no clipping phenomenon happens and the V_{out} due to V_{in} waveform was not at saturated value at all. This is as expected as the experimental gain was determined to be 1.55 for this amplifier and V_{in} = 3V (Peak-Peak from -1.5V to 1.5V, offset = 0). Thus the max V_{out} = 2.325V and min V_{out} = -2.325V, which is way lower than the saturated value of 12.936V and -12.936V determined above in 2.1.a.
- Polarity wise, **the V_{out} waveform is in phase with the V_{in} waveform**. This is the expected behaviour for an non-inverting amplifier with a positive gain.
- Amplitude wise, **the V_{out} waveform's amplitude is 1.55 times the V_{in} amplitude** (consistently throughout the waveform). This is because the gain of this amplifier configuration has magnitude > 1 so the amplitude change should be more than unity, equal to the magnitude of voltage gain = 1.55 as determined.

- **The waveform of input and output is continuous and V_{out} change linearly** with V_{in} value, shown by the corresponding sinusoidal waveform correspond to that of V_{in}.

2.3. Unity Gain Amplifier

a. Circuit Configuration with DC Power Supply as Input

The set up for Unity Gain Amplifier circuit with DC Power Supply is shown below in figure 9 based on the lab manual.

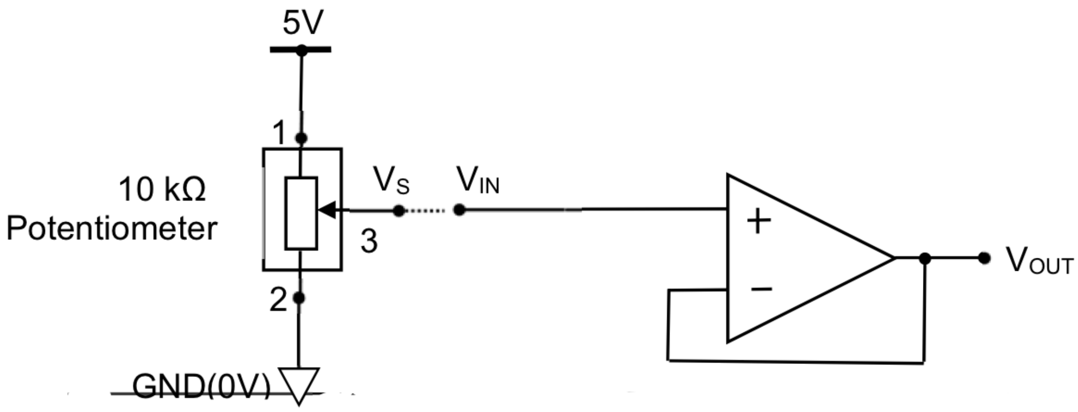

Figure 9 Unity Gain Amplifier Set-up (with DC Input)

Task 1: Measure V_{out}, V_{in} for values of V_{in} from 0V to 5V in 1V intervals. Plot V_{out} against V_{in} to derive the voltage gain of Unity Gain amplifier.

As **Unity Gain Amplifier is basically a non-inverting amplifier with short circuit in place of R_1**. We can reuse the formula (3) and (4) described in 2.2.a.

We turn the potentiometer (knob) around to vary the V_{in} value. Using a Digital Multimeter to measure V_{out} and V_{in} at V_{in} = 0V, 1V, 2V, 3V, 4V, 5V.

- From (3), **calculate voltage gain of the unity gain amplifier = 1 + (0/18) = 1 (as s/c means resistance = 0)**
- From (4), $V_{out} = V_{in}$. If after calculation $V_{out} > 15V$, $V_{out} = 15V$ and if $V_{out} < -15V$, $V_{out} = -15V$ (**theoretical saturation voltage is cap at +15V and -15V due to constraint of power supply**)
- The result of measurement for V_{out} at different interval of V_{in} as well as the corresponding calculated V_{out} is shown in table 4.

V_{in}	V_{out}(measured)	V_{out}(calculated)	Difference (absolute value)
0.000 V	0.000 V	0.000 V	0.000 V
1.000 V	1.000 V	1.000 V	0.000 V
2.001 V	2.002 V	2.001 V	0.001 V
3.002 V	3.002 V	3.002 V	0.000 V
4.001 V	4.001 V	4.001 V	0.000 V
5.001 V	5.001 V	5.001 V	0.000 V

Table 4. Vout measured vs theoretically calculated for unity gain amplifier

- Based on the V_{out} measured at the 6 intervals of V_{in}, we plot V_{out} against V_{in} and obtain a graph as shown in figure 10. This is also the best-fit line.
- From figure 7, take two points **(0.50, 0.50)** and **(4.50, 4.50)** which is in range where the op-amp output is not saturated yet. The gradient of the plot in this unsaturated range is $\frac{4.50-0.50}{4.50-0.50} = 1.00$. **Thus, actual voltage gain of this non-inverting amplifier configuration = 1.00.**

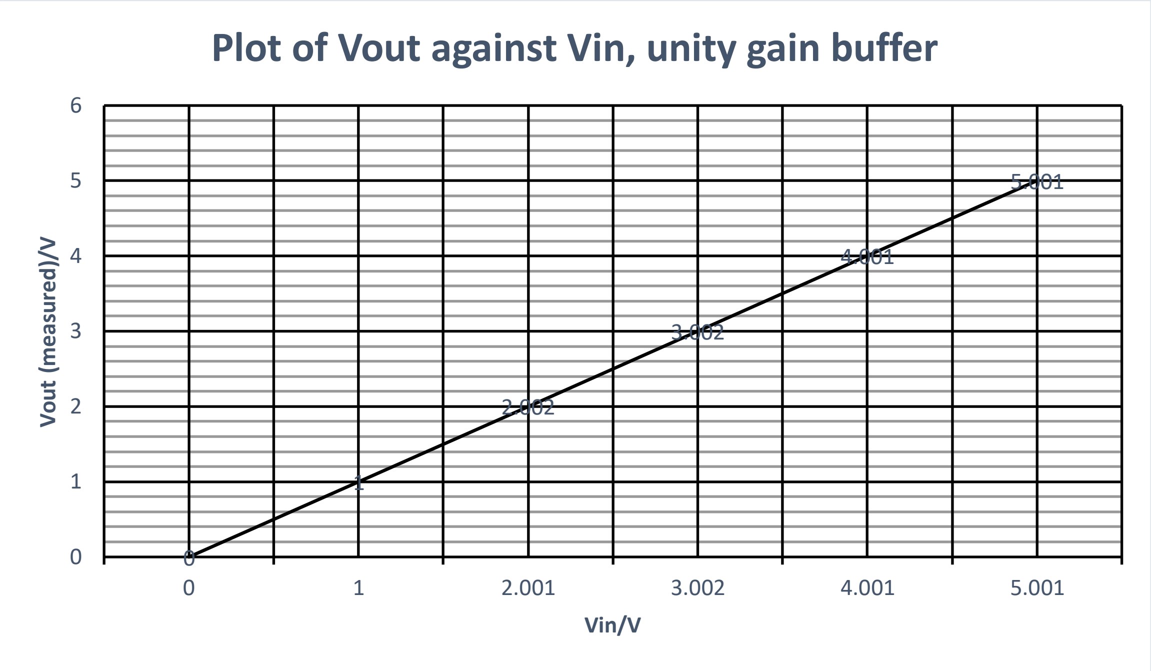

Figure 10 Plot of Vout against Vin, unity gain amp

Observations:

- **Actual voltage gain of unity amplifier is relatively close and consistent** with the theoretically predicted value and has **very high precision** (< 5.00% of error). Actual gain = 1.00 vs calculated gain = 1.00. Percentage error is 0%.
- The **voltage gain of unity gain amplifier is non-negative**, the output voltages' polarity is in phase with input voltages. This is as expected from the theoretical derived voltage gain since we are using the non-inverting amplifier to implement the unity gain buffer in this task, which is known to produce same output value with no change in polarity compared to input.
- **No saturation range in output** as max V_{out} recorded = 5.001V and is way lower than the saturated voltage level determined in part 2.1.a
- **The non-inverting amplifiers in our experiment behaves linearly** like expected . At every input interval, the output voltage is same as input. The gradient of the plot is a nice linear model, with very big linear region (no sharp swing of value of output voltage from 0 to saturated value).

b. Circuit Configuration with Sinusoidal Signal as Input

Task 3: Connect V_{IN} to the output of a function generator. Connect the -ve terminal of the function generator to GND of the power supply (not to -15V). Set the function generator to supply a 1KHz sine wave of $3V_{PK-PK}$ amplitude. Observe the waveforms at V_{IN} and V_{OUT} on the oscilloscope and sketch the waveforms.

Following the procedure described above, make the change to figure 6 circuit configuration. We can obtain the waveform as shown in figure 11.

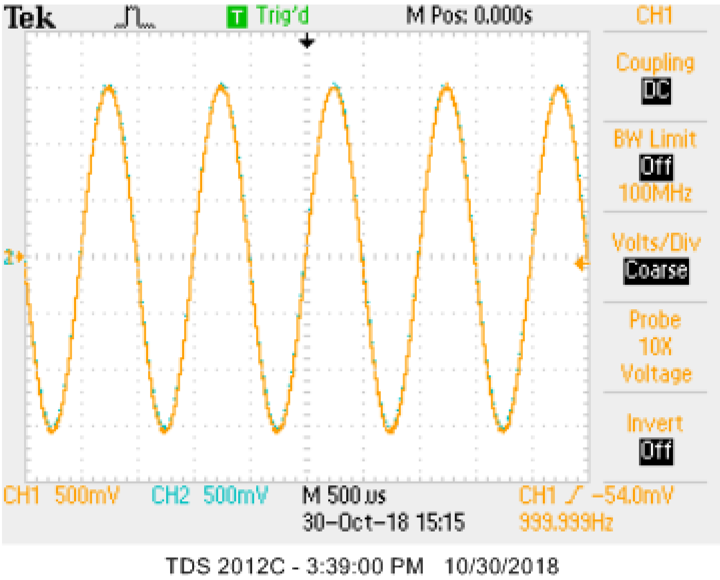

Figure 11 Waveform of Vout (blue) vs Vin (yellow) for unity gain amp

- **V_{out} waveform obtained is a complete sinusoidal waveform.** This shown that there were no clipping phenomenon happens and the V_{out} due to V_{in} waveform was not at saturated value at all. This is as expected as the experimental gain was determined to be 1.00 for this amplifier and V_{in} = 3V (Peak-Peak from -1.5V to 1.5V, offset = 0). Thus the max V_{out} = 1.5V and min V_{out} = -1.5V, which is way lower than the saturated value of 12.936V and -12.936V determined above in 2.1.a.
- Polarity wise, **the V_{out} waveform is in phase with the V_{in} waveform**. This is the expected behaviour for a non-inverting amplifier and so is unity gain buffer with a positive gain.
- Amplitude wise, **the V_{out} waveform's amplitude is equal to the V_{in} amplitude** (consistently throughout the waveform such that we cannot see V_{out} as its waveform is hidden behind the waveform of V_{in}). This is due to the unity gain thus V_{out} = V_{in} for whole waveform of V_{in}.
- The **waveform of input and output is continuous and V_{out} change linearly** with V_{in} value, shown by the corresponding sinusoidal waveform correspond to that of V_{in}.

3. Conclusions

In summary, **the 3 amplifiers** (inverting, non-inverting and unity gain amplifiers) being investigated in this experiment is **very close to ideal and behave consistently to what we have studied in class.**

Non-inverting and unity gain amplifiers both have very high (close to infinity) input impedance while this is not the case for inverting amplifiers (whose input impedance = R_1, shown in 2.1.a experiment). Thus, there will be a voltage loss from V_{Supply} going into the inverting terminal of this amplifier due to current drawn across R_1. This result in lower V_{in} received by the amplifier than the expected (should be = to V_s) as discovered in the experiment.

The saturated voltages value of the amplifiers in this experiment is capped at ±12.936V instead of ±15V. This is due to the voltage decay happening in all non-ideal, practical amplifier, thus the max voltage output will always be about 2.000V below the max voltage supply (±15V).

All amplifiers in this experiment **behaves linearly** as expected and has a very wide linear region, thus the problem of output voltage swinging from one saturated value to another with a very small change in V_{in} is not very significant (however, this is the case for inverting amplifiers for very high R_f value to R_1 value ratio, illustrated in experiment 2.1). This is shown when we investigate the behaviour of all amplifiers' output when the input is a sinusoidal waveform. In these cases, none of the amplifiers have clipping behaviour waveform (as long as reasonable level of input used).

Different amplifiers with different gain value (≥0 for non-inverting amplifiers (including unity gain) and <0 for inverting amplifiers**) can be combined to form more complex circuit of different purposes** (depend on application requirements). In these cases, the loading effect is minimal.