Summary

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Introduction

Objectives:

- Describe the workings of the operational amplifier and to show the differences between the inverting and non-inverting amplifier.
- Observe of the differences between the theoretical and measured gain of the inverting and non-inverting amplifier.
- To take note of the effect of an increase in the input voltage for inverting and non-inverting amplifiers.
- Look into the effect of adding a diode to the inverting amplifier circuit.
- Show that output voltage = A (V+ - V-).
- Show that the closed-loop gain A of the inverting amplifier is given by:

  $$A = \frac{V_o}{V_i} = \frac{-R_f}{Ri}$$

- Show that the output voltage: $V_{out} = -V_1 R_0 / R_1$
- Explain why the output voltage is always less than the input voltage.

Background

Operational amplifiers can be used to perform mathematical operations on voltage signals such as inversion, addition, subtraction, integration, differentiation, and multiplication by a constant. Understanding the workings of the operational amplifier will enable the design of circuits to be carried out effectively. Knowing the functionality and components of the op amp will enable the user/designer to understand their uses and limitations.

Theory

Basic concepts:

The operational amplifier is a *differential amplifier*. The input labelled "+" is referred to as the non-inverting input, and the input labelled "-" is referred to as the inverting input. The operational amplifier amplifies the difference between the non-inverting input and the inverting input. In other words, the output of the operational amplifier is:

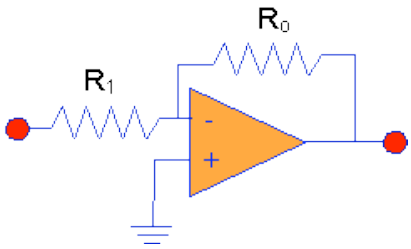
- Op-amp output voltage = A (V_+ - V_-) where
  - A is the gain - usually a pretty large number, often greater than 100,000 or 200,000.
  - V_+ is the voltage at the non-inverting input (measured to ground).
  - V_- is the voltage at the inverting input (measured to ground).

Inverting Amplifier

An operational amplifiers purpose is to amplify a weak signal and this is called Gain.
The closed-loop gain A is given by:

$$A = \frac{V_o}{V_i} = \frac{-R_f}{Ri}$$

This circuit below amplifies a voltage by a factor ($-R_o / R_1$). What is important in this circuit is that it amplifies by almost exactly ($-R_o/R_1$) so that the gain of the circuit can be controlled precisely by controlling the resistor values precisely.

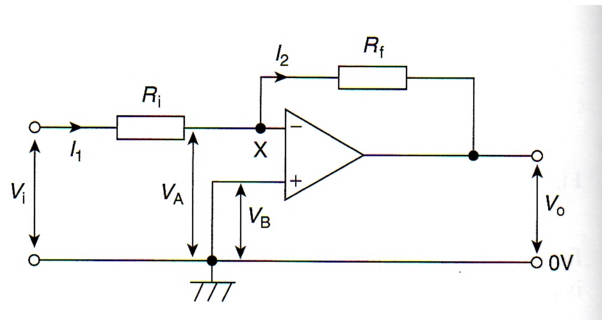


Where $R_0=-R_f$, and $R_1=R_i$

This shows that the gain of the amplifier depends only on the two resistors.
For example, if:

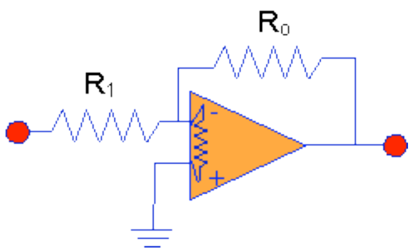
$$A=\frac{-R_f}{R_i}=\frac{-100\times10^3}{10\times10^3}=-10$$

Thus the input of 100mV will cause an output change of 1V (reference Bird p.292)



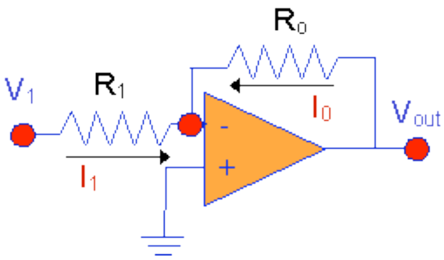
If there is a gain of 10, for instance, if 1.0V is put in then the output will be 10.0V, (R_F=Feedback resistance). Thus, we can figure out what input voltage caused what output voltage by calculating the input difference, ($V_+ - V_-$).
We assume that V_{out} is some 'reasonable value' - a value somewhere between the values of the positive and negative power supply voltages, which is just a consequence of a very high gain. The difference between inverting and non-inverting input voltages is assumed to be 0V, therefore, because of an assumed infinitely high gain (infinite gain assumption).

Since the difference between the operational amplifier input voltages are practically zero and the internal input resistance is very large, we can make the assumption that the current flowing into the amplifier through either of the input terminals is so small as to be negligible.
A modified circuit diagram that shows the input resistance of the operational amplifier.



We can then write KCL at the inverting node using the assumption that the voltage at the amplifier input - at the input node - is zero.

$$I_1 + I_0 = 0$$



We can write KCL in terms of all the voltages involved (taking V_+ and V_- as the voltages - with respect to ground - at the "+" and "-" terminals respectively):

$$(V_1 - V_-)/ R_1 + (V_{out} - V_-)/ R_0 = 0$$

However, since we assume that there is no voltage difference between V_+ and V_- , we can replace V_- with V_+ and we have the inverting input terminal connected to ground, so $V_- = 0$:

$$V_1 / R_1 + V_{out} / R_0 = 0$$

- The situation where V_+ ~= 0 is called a virtual ground.

We can then solve for the output voltage:

$$V_{out} = - V_1 R_0 / R_1$$

Symbols Used:
V: voltage, volts(V)
R: resistor, ohms(Ω)
I: current, amps(A)
A: gain, no unit
s: seconds, (s)

Experiments

Apparatus:

Scope Tektronix TDS 1002 allows signal voltages to be viewed as two-dimensional graphs of one or more electrical potential differences (vertical axis) plotted as a function of time or of some other voltage (horizontal axis).
Function generator TTi R5 is used to generate electrical waveforms.
Tti EB2025T Triple Output PSU is a bench power supply for applications requiring stable and controllable sources of DC voltage.

Procedure: *Inverting Amplifier.*

Voltage Gain:

- A theoretical value for the voltage gain of the amplifier was calculated using Equation 2.
- The oscilloscope was used to measure V_{IN} and V_{OUT} and determined the measured gain of the amplifier, using Equation 1 and peak to peak values of V_{IN} and V_{OUT} .
- The measured and theoretical gains were compared.
- Phase shift between V_{IN} and V_{OUT} were noted.

Effect of increase of V_{IN}:

- Peak to peak value of V_{IN} and V_{OUT} were noted as V_{IN} was gradually increased.

- Waveform was sketched, and magnitudes labelled.

<u>Addition of Diode</u>:

- Waveform was sketched, and magnitudes labelled. An increased scale on the oscilloscope showed detail of effect of diode in reverse bias.

Procedure: *Non-inverting Amplifier*.

<u>Voltage Gain</u>:

- A theoretical value for the voltage gain of the amplifier was calculated using Equation 2.
- The oscilloscope was used to measure V_{IN} and V_{OUT} and determine the measured gain of the amplifier, using Equation 1 and peak to peak values of V_{IN} and V_{OUT}.
- The measured and theoretical gains were compared.
- Phase shift between V_{IN} and V_{OUT} were noted.

<u>Effect of increase of V_{IN}</u>:

- Peak to peak value of V_{IN} and V_{OUT} were noted as V_{IN} was gradually increased.
- Waveform was sketched, and magnitudes labelled.

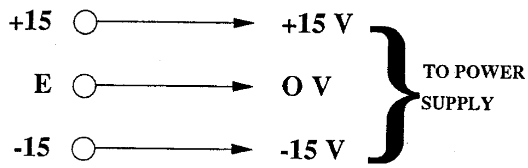
Results

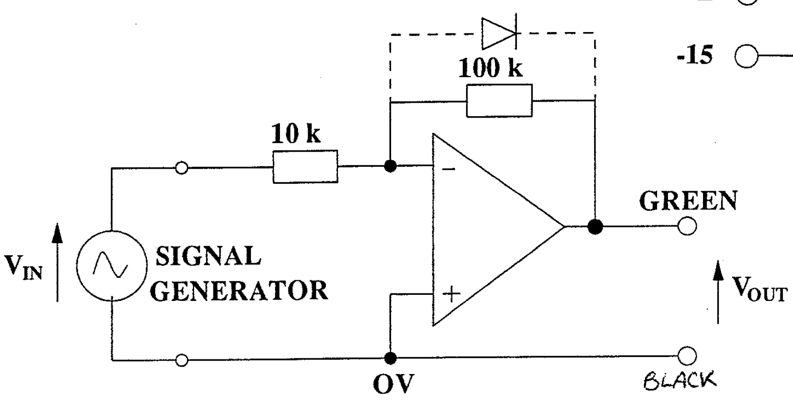
<u>Processing of data</u>

Inverting op-amp voltage gain	**Non-inverting op-amp voltage gain**
Eqn 2, $Gain = -\frac{R_F}{R_{IN}} = -\frac{100k\Omega}{10k\Omega} = 10$ $V_{IN} = 2.0V,\ V_{OUT} = 18.6V$ $Gain = \frac{V_{OUT}}{V_{IN}} = \frac{18.6V}{2.0V} = 9.3$	$\text{Theoretical gain} = 1 + \frac{R_F}{R_{IN}} = 1 + \frac{10k\Omega}{10k\Omega} = 2.0$ $\text{Measured gain} = \frac{V_{OUT}}{V_{IN}} - \frac{R_{IN}+R_F}{R_{IN}} = \frac{3.80V}{2.0V} = 1.9$

<u>Presentation of data</u>

Inverting Amplifier.





– = inverting input

+ = non-inverting input

R_F = feedback resistor

R_{IN} = input resistor

Circuit connection:

The diode was disconnected initially and the power supply was set to 15V. The signal generator was set to give 2.0V peak-to-peak at a frequency of 1.0kHz.

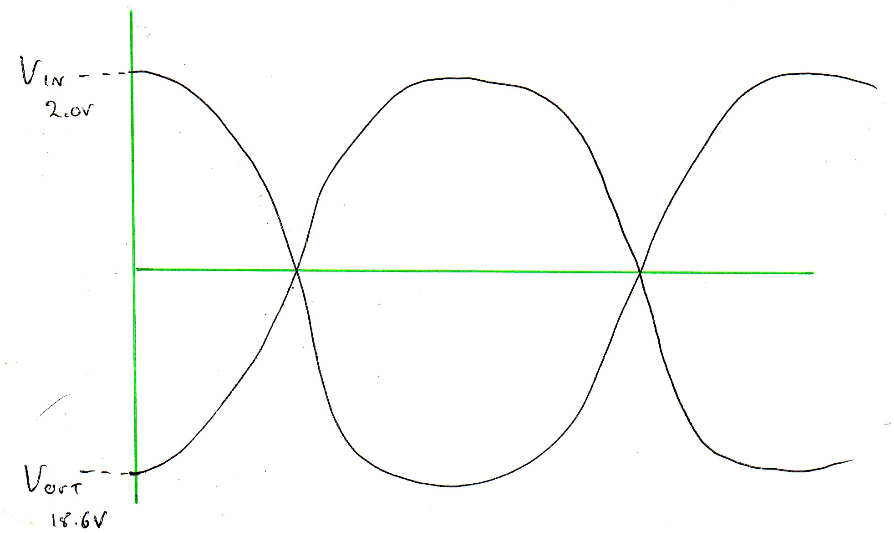
Voltage Gain:

$$\text{Eqn 2}, \quad Gain = -\frac{R_F}{R_{IN}} = -\frac{100k\Omega}{10k\Omega} = 10$$

$$V_{IN} = 2.0V, \quad V_{OUT} = 18.6V$$

$$Gain = \frac{V_{OUT}}{V_{IN}} = \frac{18.6V}{2.0V} = 9.3$$

Voltage gain (graph1) – Inverting amplifier



CH1 = V_{OUT}
1.00V
m=250μs

CH2 = V_{IN}
5.00V
m=250μs

- The theoretical gain is 0.7 higher than the measured gain. This could be due to a discrepancy in the resistors, a manufacturers margin of error or due to the quality of the components. It may also be attributed to human error when reading values from the scope.
- The waves were seen to be in anti-phase, 180 degrees difference. Neither of the waves, therefore, leads nor lags the other.

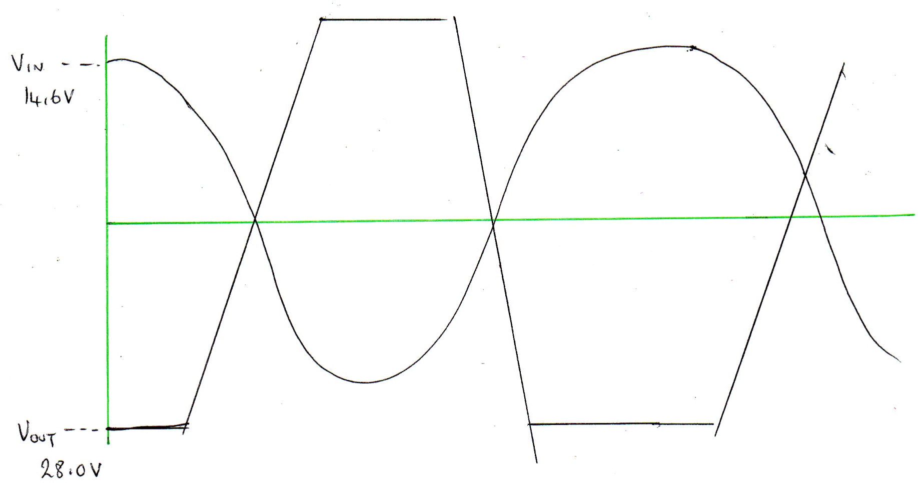
$$I_{IN} = \frac{V_{IN}}{R_{IN}}, \quad I_F = \frac{0 - V_{OUT}}{R_F}$$

$$\text{and: } I_{ZN} = I_F \quad \therefore \quad V_{OUT} = -\frac{R_F}{R_{IN}} V_{IN}$$

Effects of increase of V_{IN}

V_{OUT} = 28.0V
V_{IN} = 14.6V

Effect of increase of V_{IN} (graph2) – Inverting amplifier

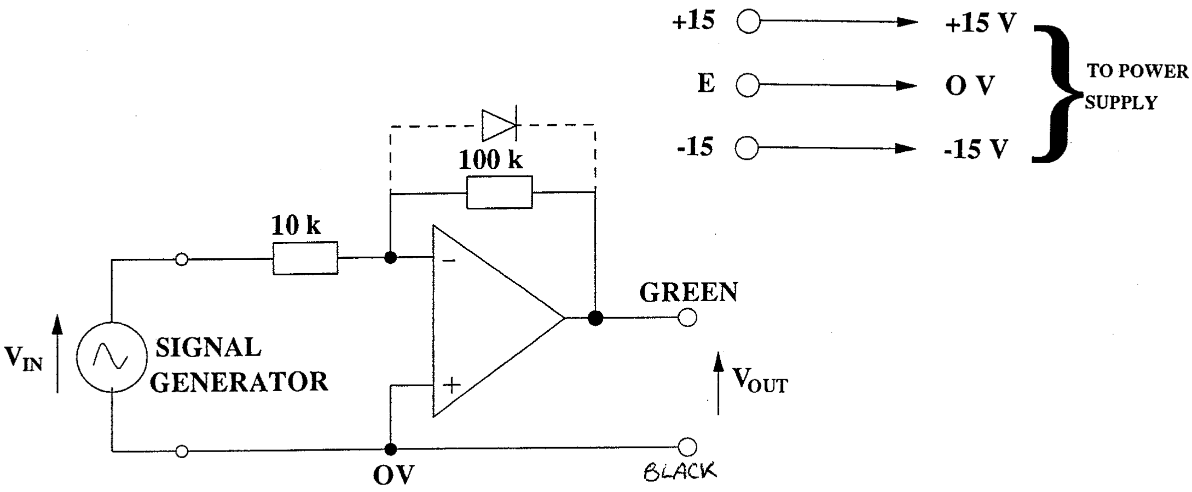


CH1 = V_{OUT}	CH2 = V_{IN}
5.00V	1.00V
m=250μs	m=250μs
28.0V peak-to-peak	2.92V peak-to-peak

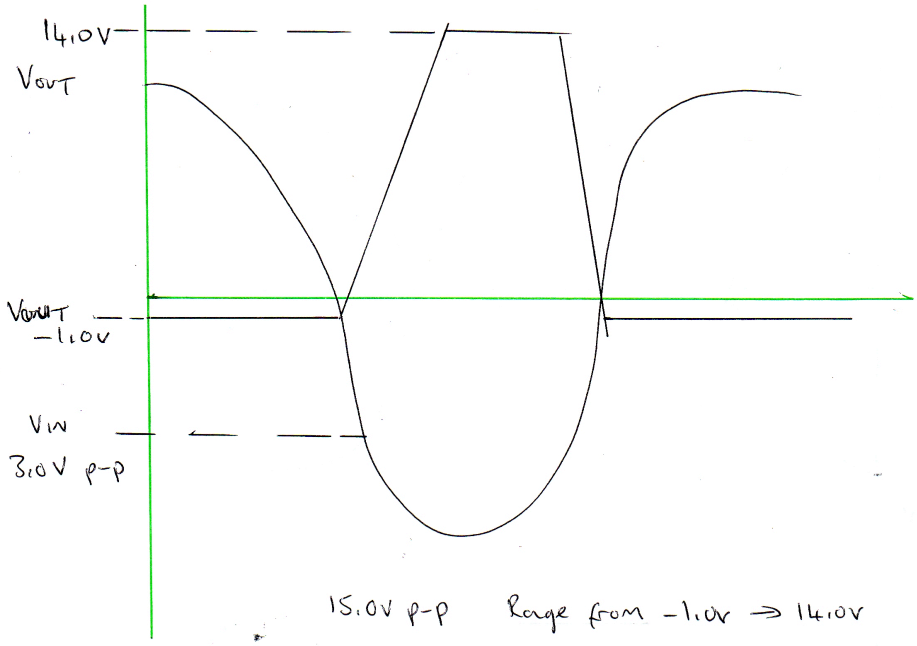
Range of voltage is ±2.92V
V_{OUT} value levels off at 28.0V as it cant' get any higher voltage than the power supply is offering. Clipping has occurred at 14.0V.

Diode Addition

As the diode starts to draw the current the voltage across R_F drops. When the diode is 0.7V, it is now opened and drawing all the current and voltage.
R_F has no voltage, therefore, and the signal bottoms out.



Addition of diode (graph3) – Inverting amplifier



CH1 = V_{OUT}	CH2 = V_{IN}
5.00V	1.00V
m=250µs	m=250µs
15.0V peak-to peak	3.0V peak-to-peak

Clipping has occurred at the expected 15.0V

Results

Non-inverting Amplifier.

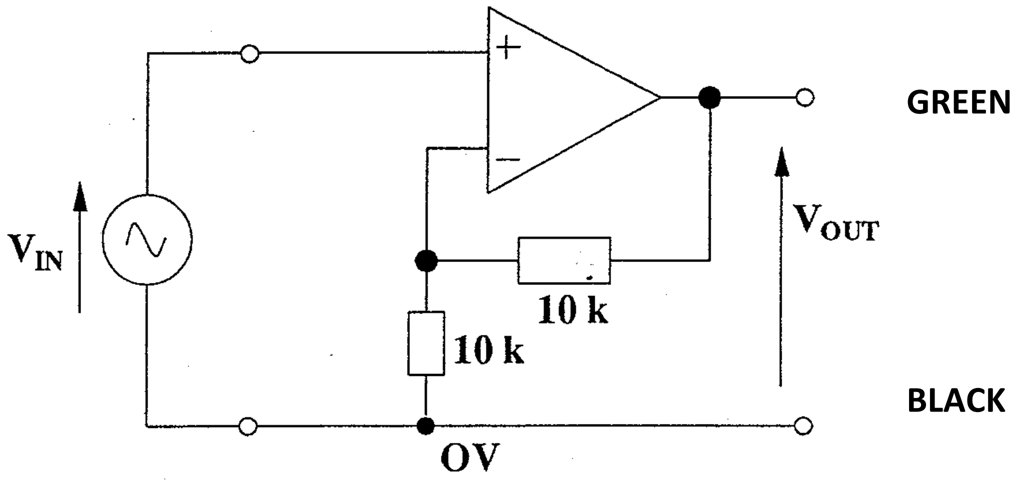


Fig.1: Inverting Amplifier

Circuit connection:

The power supply was set to 15V. The signal generator was set to give 2.0V peak-to-peak at a frequency of 1.0kHz.

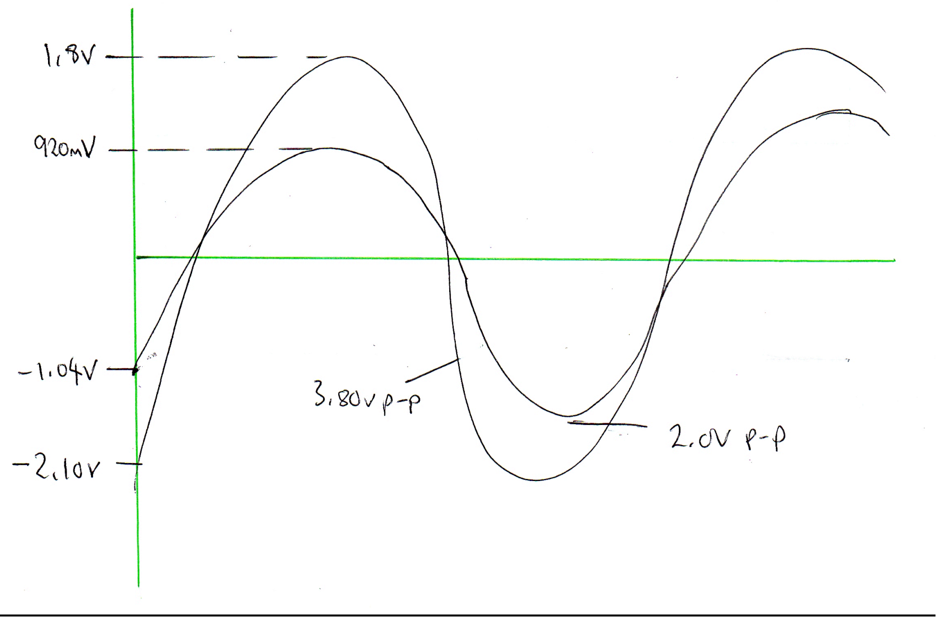
Voltage Gain:

$$\text{Theoretical gain} = 1 + \frac{R_F}{R_{IN}} = 1 + \frac{10k\Omega}{10k\Omega} = 2.0$$

$$\text{Measured gain} = \frac{V_{OUT}}{V_{IN}} - \frac{R_{IN} + R_F}{R_{IN}} = \frac{3.80V}{2.0V} = 1.9$$

- The theoretical gain is 0.1 higher than the measured gain. This could be due to a discrepancy in the resistors, a manufacturers margin of error or due to the quality of the components. It may also be attributed to human error when reading values from the scope.
- There is no phase shift on these waves = Non-inverting amplifier

Voltage gain (graph4) – Non-inverting amplifier

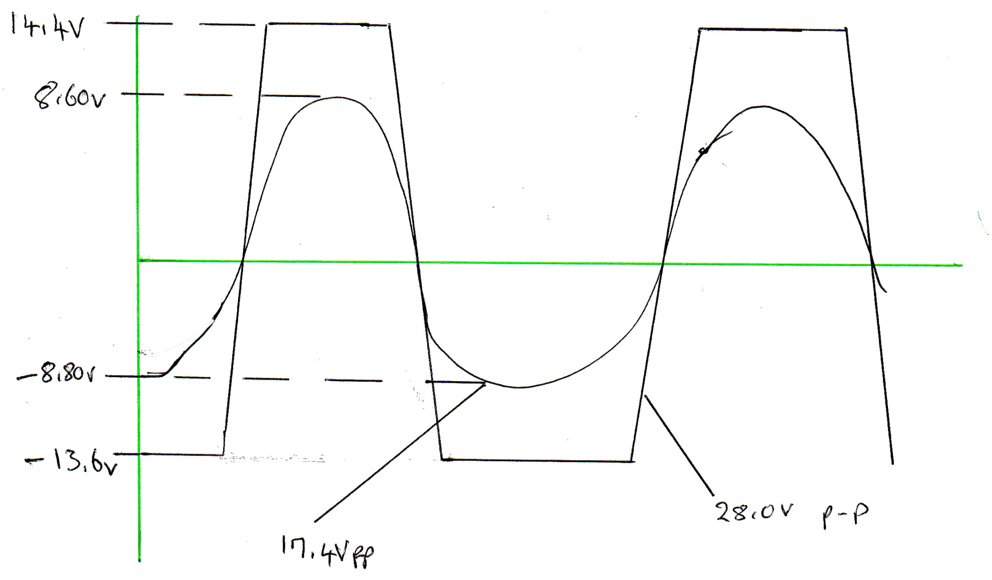


CH1 = V_{OUT}	CH2 = V_{in}
1.00V	1.00V
m=250μs	m=250μs
3.8V peak-to peak	2.0V peak-to peak

Effects of increase of V_{IN}

The waveform max's out at 14.0V due to a limit of voltage supply. When the output voltage tries to exceed the supply voltage minus the op-amp's saturation voltage , it stops rising and gets stuck.

Effect of increase of V_{IN} (graph5) – Non-inverting amplifier



CH1 = V_{OUT}	CH1 = V_{OUT}
5.00V	1.00V
m=250μs	m=250μs
28.0V peak-to peak	17.4V peak-to peak

Clipping has occurred at 14.0V.

Error analysis

In this section I'm asked to analyse the uncertainties in the processed results based on the estimated accuracy of each of the measured quantities from which they were derived. Which was the largest source of error?

For the inverting op-amp the error is 0.7V.

Percentage error = 18.6/2 =9.3

0.7/18.6x100=3.8%

0.7/2x100=35%

3.8%+35%=38.8%

0.338x9.3=3.1V

For the non-inverting op-amp the error is 0.1V.

Percentage error = 3.80/2 =1.9

0.1/3.8x100=0.03%

0.1/2x100=0.05%

0.03%+0.05%=0.08%

0.0008x1.9=0.0015V

Look at the percentage error rather than the absolute error. Hint the results for non-inverting amplifier with a gain of 2 are worse than the inverting amplifier with a gain of 10.
Are my errors the difference between theoretical and measured values. I then find percentage error from them?

Yes that's it.

Always calculate the percentage error, for example 100mV of error isn't much when the voltage is 20V, but when it's 1V, 100mV is a significant error.

I'm a bit lost with this section. Can anyone tell me what is required exactly? Are we talking about the discrepancy between the theoretical value and actual value?

The inverting and non-inverting amplifiers had estimates and measured values. The inverting was the largest discrepancy of 0.7.

So is this what I wrote earlier?:

- The theoretical gain is 0.7 higher than the measured gain. This could be due to a discrepancy in the resistors, a manufacturers margin of error or due to the quality of the components. It may also be attributed to human error when reading values from the scope.

Discussion of results

Comparison with theory

In both inverting and non-inverting amplifiers the output voltage was slightly lower than the input voltage.

Theory says that the output voltage cannot exceed the positive and negative saturation voltages. These saturation voltages are specified by an output voltage swing ratings of an op-amp for given values of supply voltage. The output voltage is directly proportional to the input difference voltage until it reaches the saturation voltages and thereafter the output voltage remains constant.

The addition of a diode to the inverting op-amp circuit caused all the current to go through

Discussion

- The circuit operates in such a way that the output is not at the exact limits set by the power supply. If we have a +12 and -12 volt set of supplies, this would probably mean that the output was limited to somewhere between -10 or -11 volts and +10 or +11 volts. In other words, it is assumed that the amplifier is operating somewhere within its linear range and is not saturated. That's what we really mean when we say that the output is some reasonable voltage.
- The output of the operational amplifier is limited by the supply used. Usually the limit is within a volt or so of the power supply voltage, so if the supply voltage is +/-12v, you might be able to drive the op-amp up to 10.8v (or something like that) and down to -10.8v. If your circuit tries to make the op-amp output voltage 17.3 v in that situation, you aren't going to see that voltage. You'll get 10.8 instead. When that happens, you say that the op-amp is saturated. Otherwise, when everything is copasetic, and the amplifier is not saturated, you say that the op-amp is operating in the linear range.

When the op-amp is operating in the linear range, then there is an expression for the output voltage in terms of the gain.

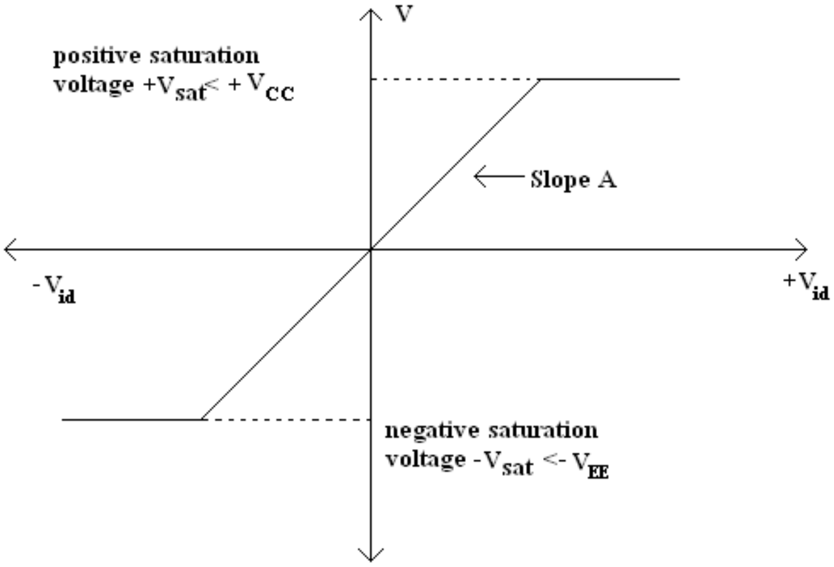
$$V_{out} = Gain*(V_{+} - V_{-})$$

where:

- V_{+} = voltage at the non-inverting input,
- V_{-} is the voltage at the inverting input,
- Gain = gain of the operational amplifier.

The gain of a 741 operational amplifier is typically well over 100,000. So, if the output is limited to something like ten (10) or eleven (11) volts, the input difference, V_{+} -V_{-}, can't be more than about 100mv (microvolts).

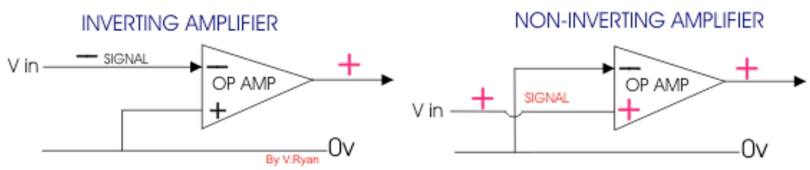
Ref(http://www.facstaff.bucknell.edu/mastascu/eLessonsHTML/OpAmps/OpAmp2.html)



ref

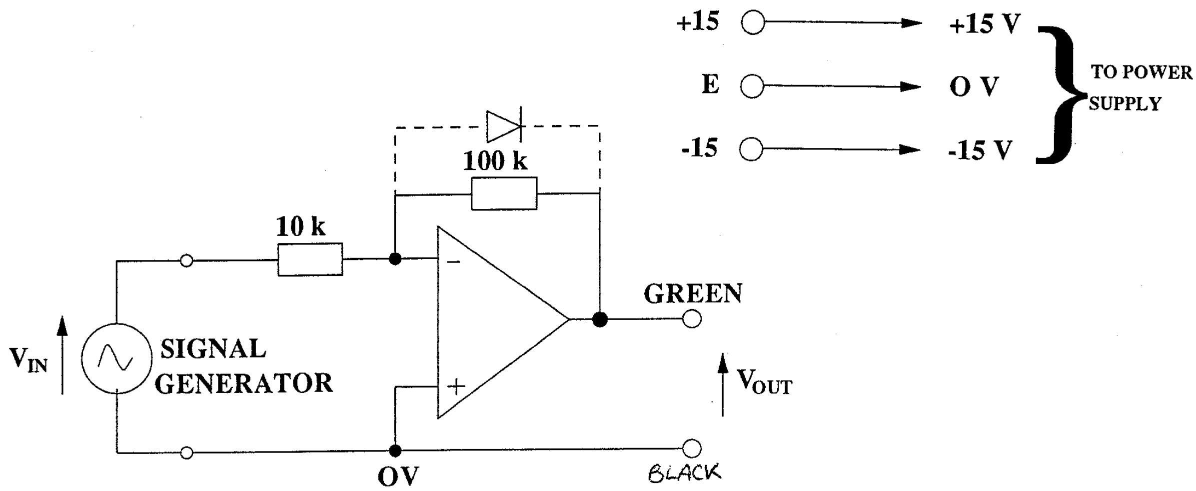
http://electricalandelectronics.org/2008/10/14/ideal-voltage-transfer-curve/

Differences between inverting and non-inverting amplifiers.



Reference (file:///Users/defunktlemon/Desktop/Non-inverting%20and%20Inverting%20Operational%20Amplifiers.html)

- For an *inverting amplifier* the polarity of a signal is reversed at the output. A negative input becomes a positive output. Voltage is applied to the inverting (-) terminal, and voltage out is therefore in anti-phase with the input. The waves will be out of phase (graph1).



- For a *non-inverting amplifier* a signal applied keeps its polarity at the output. A positive input remains a positive output. Feedback goes into the negative terminal to keep control. The signals will be in phase (graph4).

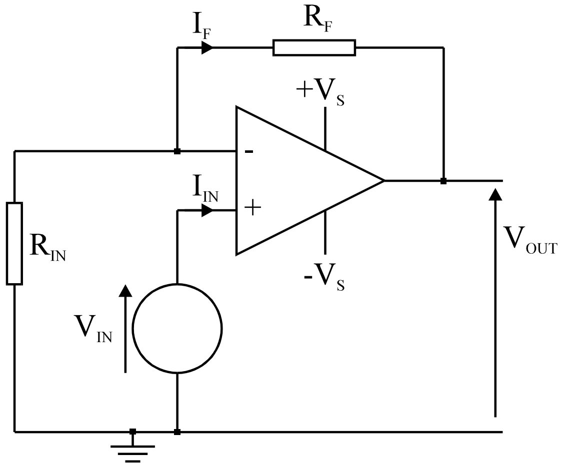


Figure 2 (a)

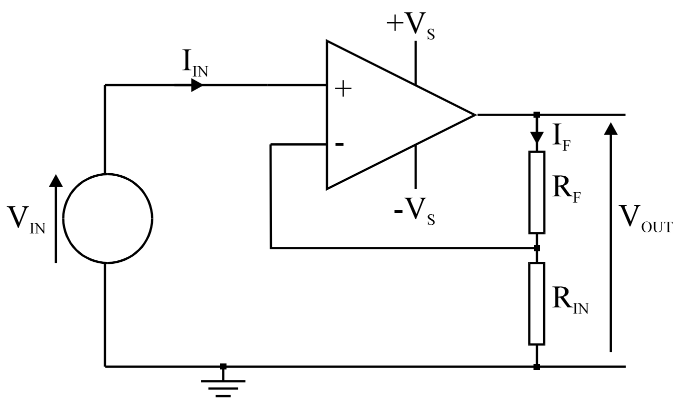


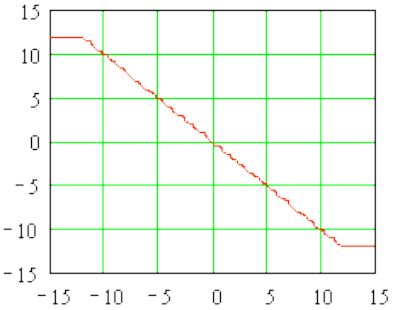
Figure 2 (b)

$$\text{Gain} = \frac{V_{OUT}}{V_{IN}} = \frac{R_{IN} + R_F}{R_{IN}} = 1 + \frac{R_F}{R_{IN}} \qquad \text{(Eqn 3)}$$

Conclusions

Whenever you use an operational amplifier, the power supply voltages limit the output voltage. Assuming there is an inverter with a gain of -2. (That is, $R_o/R_1 = 2$.) If $V_1 = 5.0$ volts, we would expect the output voltage to be -10 volts. That's probably OK. However, if $V_1 = 10.0$ volts, then we might expect the output voltage to be -20 volts. But, the output voltage can't be -20 volts. If you have power supply voltages of +/-12, it can only go as low as -10.5 or so, so that's what the output will be, -10.5 volts.

We have to conclude that the output voltage is always limited by the supply voltages, we can't make the output voltage go outside the limits set by the supply voltages. If we were to build an inverter circuit, with a gain of -1, then a plot of output versus input has to look like the one below. Without power supply limitations we would expect a straight line with a slope of -1, and we would not expect the saturation characteristic found below for the plot of output against input.



The net result is that whenever the input voltage is such that it would drive the output voltage beyond the rails, the output voltage gets clipped (does not reach a value higher than the saturation value!), and never reaches the desired value. This produces distortion in the output voltage when you try to amplify voice or music signals, for example.

References

Appendices