Unit 39 Operational amplifiers

- The following two rules are used to analyze the operation of op-amps in linear circuits:
  - **Rule 1.** When an op-amp is used in the linear region, the voltage difference between the inverting and noninverting inputs is approximately zero.
  - **Rule 2.** No current flows into the input terminals of the op-amp.
- The gain of an inverting amplifier is given by:

$$A_V = -\frac{R_f}{R_{in}}$$

The term operational amplifier or op-amp is used to describe a directly coupled amplifier fabricated as an integrated circuit on a single silicon chip. There are many types of op-amp manufactured but the most common is the 741 op-amp and this is the one which we will use. Most other op-amp types are improvements on the 741 in terms of stability, frequency response and input impedance at an increased cost.

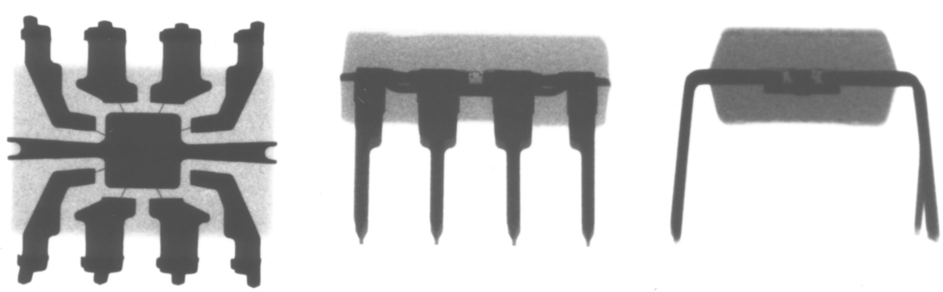

Figure 39.1: Magnified X-ray views of a 741 op-amp.

We have already met the 741 op-amp internal circuit in Problem 35.1 where you examined the internal circuit blocks of the op-amp. Figure 39.1

shows x, y and z direction X-rays of a 741 op-amp in an 8 pin dual in line (dil) package. The fine wires connecting the silicon chip mounted on the lead frame to the pins of the dil package can just be seen in the left hand X-ray. The silicon chip is mounted on the central square of the lead frame but does not show up on the X-ray as the silicon is transparent to X-rays due to the low atomic number of silicon.

It is not necessary to have a detailed knowledge of the internal circuitry of the 741 in order to use the 741. The essential feature of the 741 is that it is a directly coupled amplifier which has two inputs, an inverting input V_{in-} and a noninverting input V_{in+}. The difference between these two input voltage signals is amplified by a factor of about 10^5 or 100 dB and the amplified difference voltage appears at the single output terminal. The equation which describes the op-amp is therefore:

$$V_{out} = A_0 \left(V_{in+} - V_{in-} \right)$$

where A_0 is called the open loop gain and $A_0 \approx 10^5$. The complex circuit

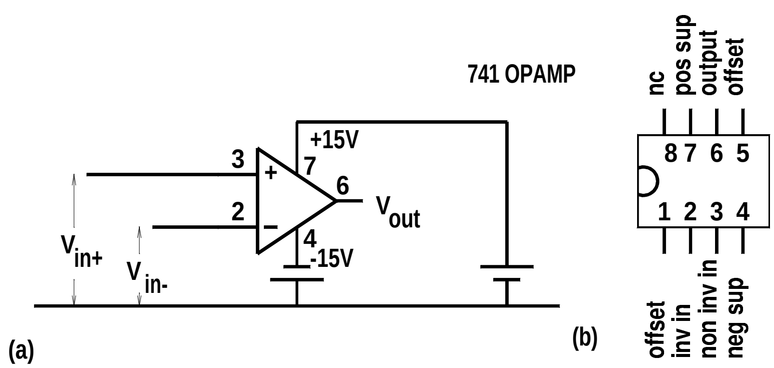

Figure 39.2: Op-amp circuit symbol and pin connections.

shown in Figure 35.5 is therefore replaced by the circuit symbol shown in Figure 39.2.(a). The integrated circuit is powered by +15 V and −15 V supplies connected with respect to the 0 V ground line, as shown. The top view of the 8 pin dil package in Figure 39.2 (b) gives the pins associated with each of the op-amp functions. The offset null function on pins 1 and 5 is used for compensating small manufacturing imbalances in the transistors in the input stages of the op-amp. We will examine this function at a later stage.

Now consider the equation for the op-amp gain given above. If we operate the op-amp in the linear region where the output voltage remains within the range ±10 V, the output voltage then corresponds to maximum input voltage differences between the two input terminals of:

$$|V_{in+} - V_{in-}| = \frac{10\,\mathrm{V}}{A_0} = \frac{10}{10^5} = 10^{-4}\,\mathrm{V} = 100\,\mu\mathrm{V}$$

which is small. In typical use the difference of the voltages at the input terminals will usually be much smaller than this so we then obtain the rule that *when an op-amp is used in the linear region, the voltage difference between the inverting and noninverting inputs is approximately zero.* The voltage difference is not exactly zero, otherwise we would never get an output voltage from the op-amp, but it is negligible compared to the voltages normally applied to the amplifier circuit. It is important always to make a distinction between the op-amp and the amplifier circuit which uses an op-amp as a component.

The op-amp has been designed to have an input resistance between the inverting and noninverting inputs of at least $1\,\mathrm{M}\Omega$. We have just seen that the typical voltage difference between the two input terminals is not greater than $100\,\mu\mathrm{V}$ when the op-amp is operating in the linear region. This means that the current flowing into the input terminals is less than $\frac{100\,\mu\mathrm{V}}{10^6\,\Omega} = 10^{-10}\,\mathrm{A}$. This current is so small as to be negligible. We therefore have our second approximation rule: *no current flows into the input terminals of the op-amp.*

These two rules for op-amp operation in the linear region permit nearly all op-amp circuits to be analyzed and give a tremendous simplification of the analysis of op-amp circuits as compared to the problems of analysis of discrete transistor or FET circuits.

We will now examine how these rules can be used to analyze an inverting amplifier such as that shown in Figure 39.3 (a).

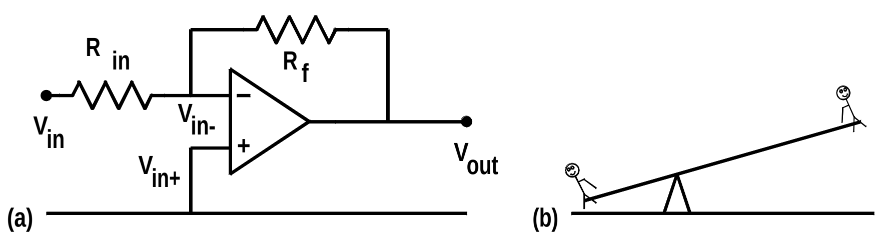

Figure 39.3: Inverting amplifier circuit and model.

The negative power supply connection at pin 4 and the positive power supply connection at pin 7 have been omitted from the diagram but not from the actual circuit in order to avoid cluttering up the diagram. This convention will be followed in the remainder of the text. Another point of note is that the circuit can be drawn with either the inverting input (−) or the noninverting input (+) at the top of the op-amp symbol depending on which configuration gives greater clarity and simplicity in the circuit diagram.

Two resistors, R_{in} and R_f, are used in the circuit. A voltage, V_{in}, is applied at the input to the amplifier. We are using the op-amp in the linear region (which implies that we are using negative feedback which we will discuss in Unit 41) and therefore the first rule for op-amps applies — the voltage difference between inverting input and noninverting input is approximately zero.

$$V_{in-} \approx V_{in+} = 0\,\mathrm{V}$$

The second rule tells us that all of the current flowing though R_{in} also flows through R_f because no current flows into the inverting input of the op-amp. This then gives us:

$$I_{in} = I_f$$

but by using Ohm's law we have:

$$\begin{aligned}
\frac{V_{in} - V_{in-}}{R_{in}} &= \frac{V_{in} - 0\,\mathrm{V}}{R_{in}} = I_{in} \\
\frac{V_{in-} - V_{out}}{R_f} &= \frac{0\,\mathrm{V} - V_{out}}{R_f} = I_f \\
\text{Therefore} \quad \frac{V_{in}}{R_{in}} &= -\frac{V_{out}}{R_f} \\
\text{or} \quad A_V &= \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}
\end{aligned}$$

This gives us an amplifier which has a voltage gain which is determined by the ratio of two resistors. The negative sign tells us that it is an inverting amplifier.

A very good analogy for this circuit is the seesaw shown in Figure 39.3 (b). The pivot point of the seesaw does not move and this is the analog to the first rule. The ratio of the movement of the two children is the inverse of the ratio of the lengths of the two sides of the seesaw. This is the analog to $A_V = -\frac{R_f}{R_{in}}$. One child goes up, the other child goes down. This gives the negative sign corresponding to this inversion of movement.

39.1 Example

39.1 An inverting amplifier powered from a dual $\pm 15\,\mathrm{V}$ supply has $R_{in} = 10\,\mathrm{k\Omega}$ and $R_f = 150\,\mathrm{k\Omega}$. Calculate the gain of the amplifier and plot a graph of the output voltage when V_{in} is varied from $-2\,\mathrm{V}$ to $+2\,\mathrm{V}$.

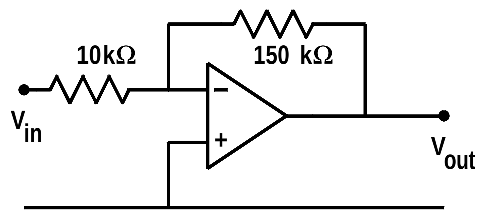

Figure 39.4: Example 39.1. Inverting amplifier.

The gain of this circuit is $A_V = -\frac{150\,\mathrm{k\Omega}}{10\,\mathrm{k\Omega}} = -15$.

Now calculate a number of representative values for the output given by $V_{out} = -15 \times V_{in}$:

V_{in}	Calculated V_{out}	Actual V_{out}
-2 V	$+30$ V	$+13$ V
-1 V	$+15$ V	$+13$ V
-0.8 V	$+12$ V	$+12$ V
-0.5 V	$+7.5$ V	$+7.5$ V
0 V	0 V	0 V
$+0.5$ V	-7.5 V	-7.5 V
$+0.8$ V	-12 V	-12 V
$+1$ V	-15 V	-13 V
$+2$ V	-30 V	-13 V

These calculations are plotted in Figure 39.5. It should be noted that the op-amp goes into saturation for output voltages about 2 V less than the supply voltages which are ±15 V in this case. This gives saturation at ±13 V output.

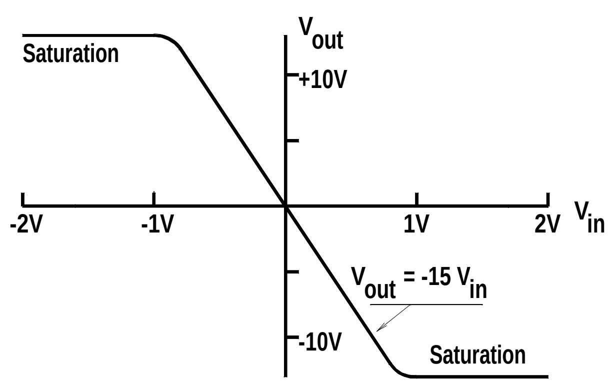

Figure 39.5: Output voltage as a function of input voltage for Example 39.1.

39.2 Problems

39.1 A 10 kΩ potentiometer can be rotated from 0° to 270° and is connected between the +15 V and −15 V supplies. Calculate the output voltage as a function of the angle of rotation. Can the output voltage ever be greater than +15 V or less than −15 V?

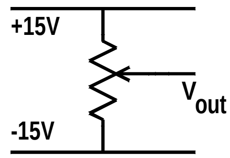

Figure 39.6: Problem 39.1.

39.2 Explain why the output voltage from an amplifier powered from a ±15 V supply can never be greater than +15 V or less than −15 V.

39.3 Calculate the voltage gain of the amplifier shown in Figure 39.7. Plot the output voltage as a function of input voltage for input voltages between −1 V and +1 V. The op-amp is powered from a dual ±12 V supply which is not shown in the circuit diagram.

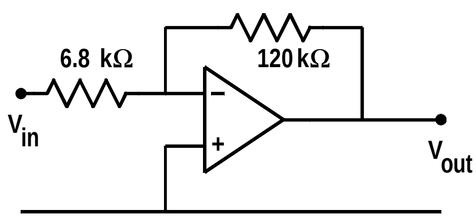

Figure 39.7: Problem 39.3.

39.4 Calculate the current which flows in the 120 kΩ feedback resistor in Figure 39.7 when the input voltage is +0.35 V.

39.5 If the 6.8 kΩ, R_{in} and the 120 kΩ, R_f, in Figure 39.7, are changed to 100 Ω and 2.5 kΩ respectively, calculate the new value of the voltage amplification. Calculate the value of the current in the R_f when the input voltage is 0.15 V.

39.6 Design an inverting amplifier which has a voltage gain of −37. Calculate the input resistance of the amplifier.

39.7 Design an inverting amplifier which has an input resistance of 12 kΩ and a voltage gain of −18.