Operational Amplifier - IC 741

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Aim: To study the working of an 741 operational amplifier by conducting the following experiments:
(a) Input bias current measurement
(b) Input offset current measurement
(c) Gain measurement in the inverting and non-inverting configurations
(d) Set up the op-amp as an integrator.

Apparatus:

Component	quantity
Operational amplifier kit	1 nos.
Connecting leads	1 set.
Function generator	1 nos.
CRO	1 nos.

1 Introduction

The term operational amplifier or "op-amp" refers to a class of high-gain DC coupled amplifiers with two inputs and a single output. The modern integrated circuit version is typified by the famous 741 op-amp. Some of the general characteristics of the IC version are:

- High gain, on the order of a million

- High input impedance, low output impedance

- Used with split supply, usually +/- 15V

- Used with feedback, with gain determined by the feedback network.

The operational amplifier (op-amp) was designed to perform mathematical operations. Although now superseded by the digital computer, op-amps are a common feature of modern analog electronics.

The op-amp is constructed from several transistor stages, which commonly include a differential-input stage, an intermediate-gain stage and a push-pull output stage. The differential amplifier consists of a matched pair of bipolar transistors or FETs. The push-pull amplifier transmits a large current to the load and hence has a small output impedance.

The op-amp is a linear amplifier with $V_{out} \propto V_{inp}$. The DC open-loop voltage gain of a typical op-amp is 10^3 to 10^6. The gain is so large that most often feedback is used to obtain a specific transfer function and control the stability.

Cheap IC versions of operational amplifiers are readily available, making their use popular in any analog circuit. The cheap models operate from DC to about 20 kHz, while the high-performance models operate up to 50 MHz. A popular device is the 741 op-amp. It is usually available as an IC in an 8-pin dual, in-line package (DIP).
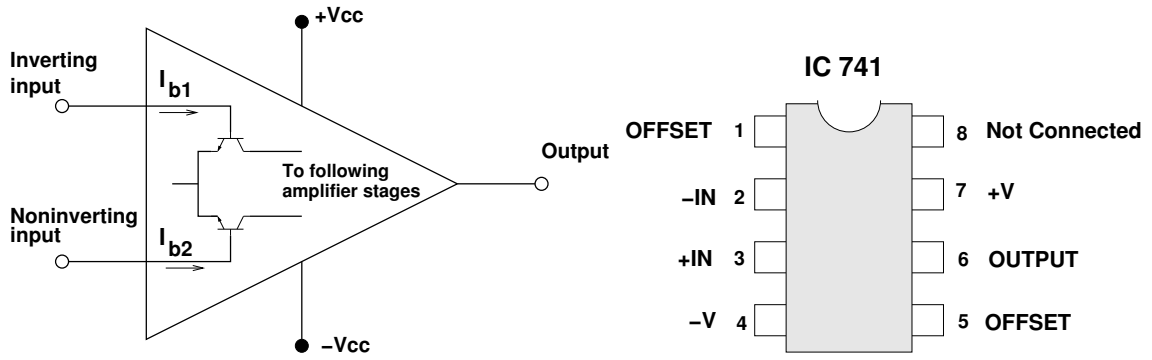
Figure 1: Operational ampifier IC 741.

2 Theoretical background

2.1 Inverting and non-inverting amplifier

Basic circuits for inverting and non-inverting amplifier are schematically shown in Fig. 2. The gain of the inverting amplifier is simply given by

$$A = -\frac{R_f}{R_1} \tag{1}$$

and the gain of the non-inverting amplifier is given by
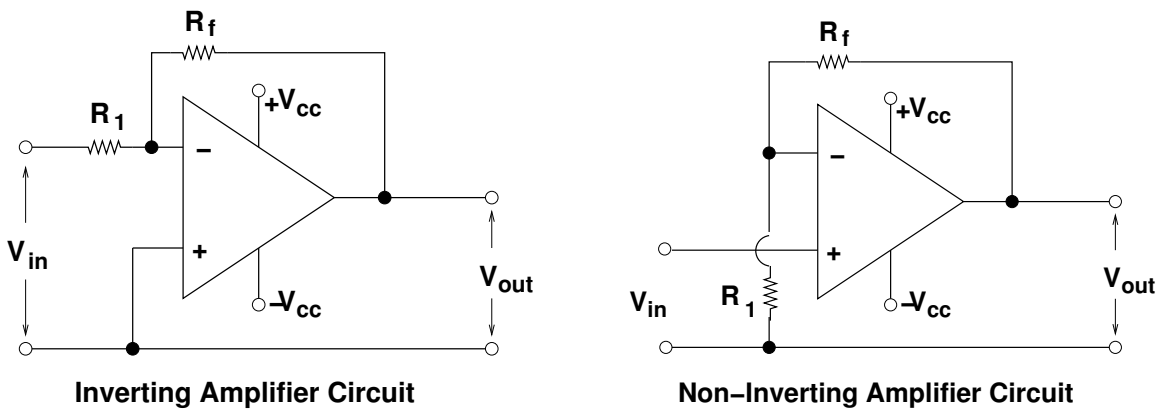
$$A = \frac{R_1 + R_f}{R_1} \tag{2}$$

Figure 2: Circuits for inverting and non-inverting amplifier.

Everything else can be calculated using equations (1) and (2).

2.2 Offset voltage

A practical concern for op-amp performance is *voltage offset*. That is, effect of having the output voltage something other than zero volts when the two input terminals are shorted together. Remember that operational amplifiers are *differential* amplifiers above all: they're supposed to amplify the

difference in voltage between the two input connections and nothing more. When that input voltage difference is exactly zero volts, we would (ideally) expect to have exactly zero volts present on the output. However, in the real world this rarely happens. Even if the op-amp in question has zero common-mode gain, the output voltage may not be at zero when both inputs are shorted together. This deviation from zero is called offset. A perfect op-amp would output exactly zero volts with both its inputs shorted together and grounded. However, most op-amps off the shelf will drive their outputs to a saturated level, either negative or positive.

Offset voltage will tend to introduce slight errors in any op-amp circuit. So how do we compensate for it? There are usually provisions made by the manufacturer to trim the offset of a packaged op-amp. Usually, two extra terminals on the op-amp package are reserved for connecting an external "trim" potentiometer. These connection points are labeled **offset null**.

2.3 Input bias current

Inputs on an op-amp have extremely high input impedances. That is, the input currents entering or exiting an op-amp's two input signal connections are extremely small. For most purposes of op-amp circuit analysis, we treat them as though they don't exist at all. We analyze the circuit as though there was absolutely zero current entering or exiting the input connections.

This idyllic picture, however, is not entirely true. Op-amps, especially those op-amps with bipolar transistor inputs, have to have some amount of current through their input connections in order for their internal circuits to be properly biased. These currents, logically, are called bias currents. Under certain conditions, op-amp bias currents may be problematic. The following circuit illustrates one of those problem conditions:

Another way input bias currents may cause trouble is by dropping unwanted voltages across circuit resistances. Take this circuit for example:
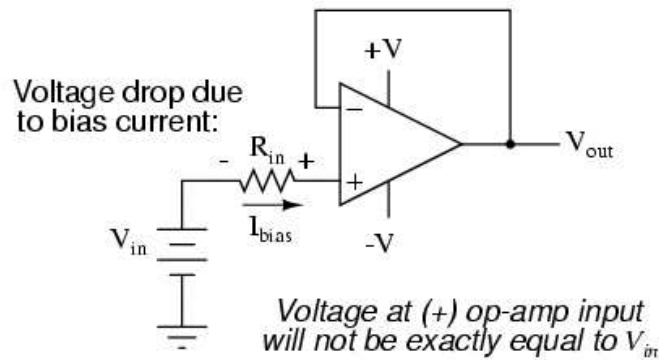
We expect a voltage follower circuit such as the one above to reproduce the input voltage precisely at the output. But what about the resistance in series with the input voltage source? If there is any bias current through the noninverting $(+)$ input at all, it will drop some voltage across R_{in}, thus making the voltage at the noninverting input unequal to the actual V_{in} value. Bias currents are usually in the microamp range, so the voltage drop across R_{in} won't be very much, unless R_{in} is very large.

2.4 Measurement of input bias current

As mentioned eralier, input bias current is very small in magnitude - so, measuring it directly is not a good idea. However, it can be measured cleverly using the following circuit.
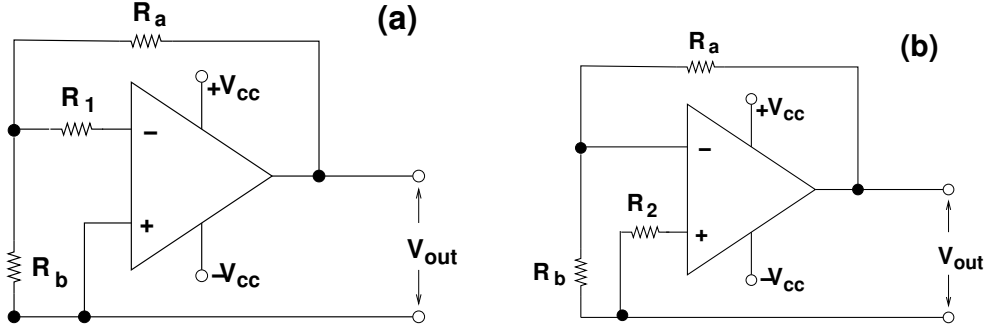

Figure 3: Circuits to measure input bias currents I_{b1} and I_{b2}, respectively.

Fig. 3(a) is just the circuit for an inverting amplifier, with the input grounded. So, the voltage at the inverting input terminal should be ideally zero. But from the circuit above, one can see that the voltage at the inverting input has two contributions - one, V_{out} reduced by the potential divider made out of R_a and R_b, i.e., $\frac{R_b}{R_a+R_b}V_{out}$ - two, the voltage drop over the R_1 if there is a non-zero input bias current flowing. Thus, we can write

$$V_i = \frac{R_b}{R_a + R_b}V_{out} - I_{b1}R_1 = 0 \tag{3}$$

or

$$I_{b1} = \frac{1}{R_1}\frac{R_b}{R_a + R_b}V_{out}. \tag{4}$$

If $R_a = 10$ kΩ, $R_b = 780\Omega$ and $R_1 = 1$ MΩ, we get

$$I_{b1} = \frac{1}{1 \times 10^6}\frac{780}{10000 + 780}V_{out} = \frac{10^{-6}V_{out}}{13.82}A = \frac{V_{out}}{13.82}\mu A. \tag{5}$$

(*In the original manual, the value of R_b is wrongly assumed to be 330 Ω, which leads to the wrong conclusion, $I_{b1} = 10^{-6}\frac{330}{10000+330}V_{out} \approx \frac{V_{out}}{31.3}\mu A$*)

Input bias current I_{b2} can be similarly measured using the circuit in Fig. 3(b), which represents a non-inverting amplifier, with the input grounded through the resistor R_2. The voltage at the non-inverting terminal would be $I_{b2}R_2$, which gets amplified to give V_{out}. Using the relation for non-inverting gain, one can write

$$V_{out} = V_i\frac{R_b + R_a}{R_b} = I_{b2}R_2\frac{R_b + R_a}{R_b}. \tag{6}$$

So, the inverting input bias current is given by

$$I_{b2} = \frac{1}{R_2}\frac{R_b}{R_a + R_b}V_{out}. \tag{7}$$

For $R_2 = 1$ MΩ, one gets

$$I_{b2} = \frac{1}{1 \times 10^6}\frac{780}{10000 + 780}V_{out} = \frac{10^{-6}V_{out}}{13.82}A = \frac{V_{out}}{13.82}\mu A. \tag{8}$$

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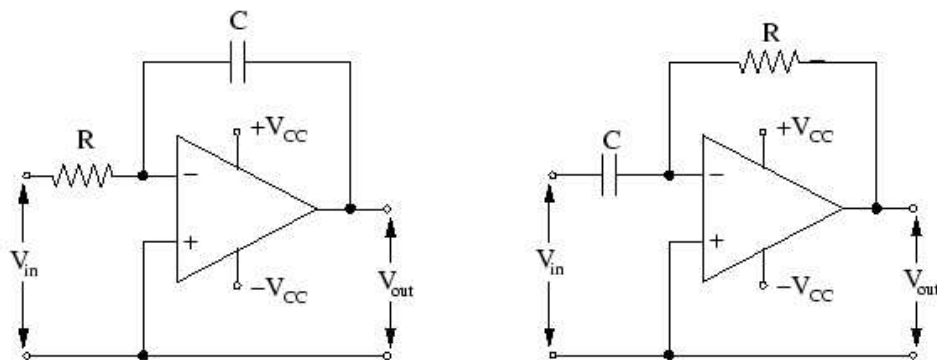## 2.5 Op-amp as integrator and differentiator

Figure 4: Circuits for setting up operational amplifier as integrator and differentiator respectively.

Operational amplifier can be setup as an integrator and differentiator using a capacitor, as shown in Fig. 4.

In the case of an integrator, the output voltage will be

$$V_{out}(t) = V_{out}(0) - \frac{1}{RC} \int_0^t V_i(t')dt' \tag{9}$$

Various kinds of input waves can be given as input. The rectangular wave, for example, will produce the following output:
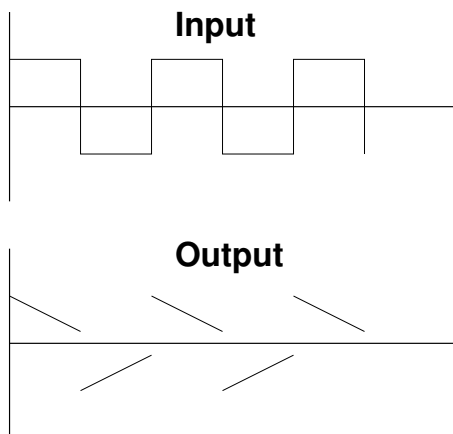
In the case of a differentiator, the output voltage will be

$$V_{out}(t) = -RC\frac{dV_i}{dt}. \tag{10}$$

3 Procedure

3.1 Input bias current measurement

1. Switch off the offset-null potentiometer.

2. Hook up the circuit shown in Fig. 3(a), by choosing R_1 to be 1M and connecting the loose end of R_1 (1) to the middle of the potential divider in the output (8).

3. Switch on the power supply and wait for two mins for the output to stabilize.

4. Measure the output voltage, and calculate I_{b1} as $I_{b1} = \frac{V_{out}}{13.82} \ \mu A$

5. Next, hook up the circtuit in Fig. 3(b) by choosing R_2 to be 1M, and connecting the inverting input to the middle of the potential divider (8).

6. Measure the output voltage, and calculate I_{b2} as $I_{b2} = \frac{V_{out}}{13.82} \ \mu A$

7. Calculate the input bias current as $I_b = (I_{b1} + I_{b2})/2$

3.2 Input offset current measurement

1. Switch off the offset-null potentiometer.

2. Set $R_1 = 1M$ and $R_2 = 1M$

3. Connect the loose end of R_1 (1) to the middle of the potential divider in the output (8). Connect the loose end of R_2 (2) to ground.

4. Switch on the power supply, wait for two mins and then measure the output voltage V_{out}.

5. Calculate the input offset current as $I_0 = \frac{V_{out}}{13.82} \ \mu A$.

6. Compare this value of I_0 with that calculated from the input bias currents, measured earlier: $I_0 = I_{b1} - I_{b2}$.

3.3 Inverting and non-inverting gain measurement

1. Set up the "inverting" configuration in Fig. 2, with $R_1 = 1K$ and $R_f = 10K$ (keep the offset-null switch off).

2. Zero input voltage should give zero output voltage. To check this, connect the free end of R_1 to ground and measure the output voltage V_{out}. The voltage won't be zero. To remedy this problem, we have to use the offset-null fascility provided in IC 741. For this, switch on the offset-null switch and adjust the potentiometer so that V_{out} is zero. Do no disturb the setting of the potentiometer in the rest of the experiment.

3. Remove the lead connecting the free end of R_1 to ground. Connect the free end of R_1 to the input voltage outlet. Apply a small voltage by turning the input voltage potentiometer, so that a large value of V_{out} is obtained. Note this V_{out}. Now connect the meter to the input voltage terminal to measure the input voltage V_i. Calculate the gain as $A = V_{out}/V_i$ and verify that its value is approximately 10.

4. Repeat the last step for three different +ve and three -ve input voltages.

5. The same configuration can be modified to set up "non-inverting" amplifier. Connect the free end of R_1 (1) to ground and the non-inverting input terminal to ground. Use the same values of R_1, R_f as in the previous setup.

6. Check if the output voltage is zero. If not, adjust the offset-null potentiometer to make it zero.

7. Disconnect the non-inverting input terminal from the ground and connect it to the input voltage supply. Apply a small voltage by turning the input voltage potentiometer, so that a large value of V_{out} is obtained. Note this V_{out}. Now connect the meter to the input voltage terminal to measure the input voltage V_i. Calculate the gain as $A = V_{out}/V_i$ and verify that it is equal to $(R_1 + R_f)/R_1$.

8. Repeat the last step for three different +ve and three -ve input voltages.

3.4   Operational amplifier as integrator

1. Set up the operational amplifier by connecting the circuit shown in Fig. 4. Use $R_1 = 1K$ and in place of R_f connect the capacitor C, which is 0.02 μF.

2. Connect the free end of R_1 (1), to a function generator producing rectangular wave.

3. Connect the output of the op-amp to a cathode ray oscilloscope (CRO).

4. Switch on the function generator and the CRO. The frequency and amplitude of the rectangular wave has to be adjusted to get a good ramp-like output on the CRO. Trace the output waveform.

5. Adjust the CRO time and voltage selector knobs to obtain a magnified graph of a single ramp.

6. Measure the maximum and minimum voltage of the ramp as V_{max} and V_{min}. Also measure the time duration of the ramp as T. Calculate $t_{RC} = \frac{T}{1 - V_{min}/V_{max}}$. The value of t_{RC} should be approximately equal to $R_1 C$.