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Operational Amplifiers and Digital Electronics.

Operational Amplifiers (Op-Amps).

1.1. Introduction

The operational amplifier in short Op-Amp is a linear Integrated circuit, also called a differential amplifier. Op-Amp is a linear and active device, which performs various operations like, signal conditioning, filtering, addition, subtraction, integration, differentiation, etc...

Op-amps are voltage amplifiers designed to be used with feedback circuits, using the elements Resistors or capacitors. The feedback elements determine the operation of the op-amps.

Op-Amps have three terminals, two input terminals named Inverting input terminal, Non-Inverting input terminal, and one output terminal. The op-Amp performs the amplification of the difference of the two input signals through +VCC and -VEE DC biasing power supply. Hence the name differential amplifier, shown in figure(1).

1.2. Circuit Symbol of an Op-Amp:

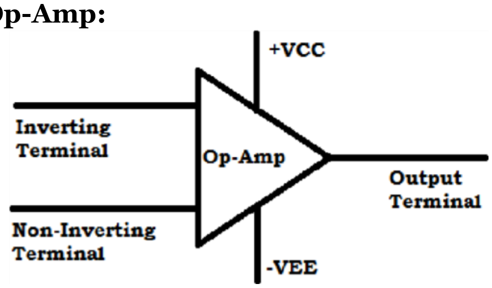
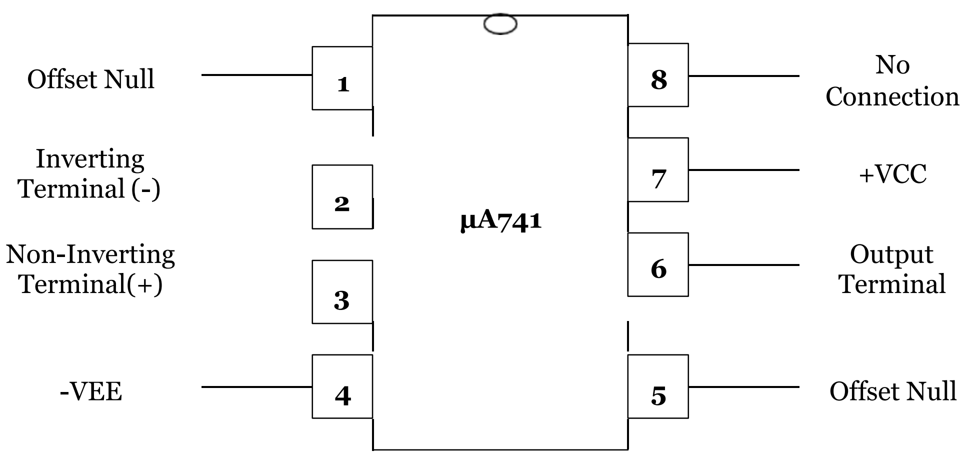


Figure 1: Circuit Symbol of an Op-Amp.

Op-amps come with an Integrated circuit(IC) package, which is an eight-pin IC, IC number is µA741.

1.3. Pin Details of µA741:

Figure(2) shows the pin diagram of IC µA741.



PINs 1 and 5 are offset null terminals, used to calibrate the op-Amp. Pin 2 is inverting input terminal, pin 3 is the non-inverting terminals, pin 6 is the output terminal, pin 4 and 7 are power supply terminals -VEE and +VCC respectively, and Pin 8 is no connection(NC) reserved for future enhancement.

1.4. Ideal Characteristics of Op-Amp:

i) Infinite Voltage Gain/loop gain

Voltage gain is the ratio of output voltage to the input voltage.

i.e., $A_v = \frac{V_{out}}{V_{in}}$

NOTE: Ideally ∞, typically $2x10^5$. **ii) Infinite input impedance**

Input impedance is the ratio of input voltage to the input current, an Op-amp, the input current is zero., Hence, the Input impedance is infinite.

i.e., $Z_i = \frac{V_{in}}{I_{in}}$

NOTE: Ideally ∞, typically 1MΩ-2 MΩ. **iii) Zero output Impedance**

Output impedance is the ratio of output voltage to the output current, in op-amp output current is maximum. Hence, the output impedance is zero.

i.e., $Z_o = \frac{V_{out}}{I_{out}}$

NOTE: Ideally 0, typically 50-75 Ω. **iv) Infinite Bandwidth**

An op-amp has an infinite frequency response and can amplify the signal from DC to the highest frequencies.

NOTE: Ideally ∞, typically few GHz.

v) Infinite Common Mode Rejection Ratio(CMRR)

CMRR is the ratio of differential gain to the common-mode gain., Common-mode gain is the difference of the two input signals is zero. If Common mode voltage gain is zero, the CMRR is infinite. i.e., $CMRR = \frac{A_D}{A_{CM}}$

$$A_{CM} = V_{inv} - V_{non-inv} \approx 0$$

NOTE: Ideally ∞, typically 70-90dB.

vi) Zero Slew rate

Slew rate is the rate of change of output voltage, which tells how fast the system responds to the change in the input signal.

$$\text{i.e., Slew Rate} = \frac{dV_{out}}{dt}$$

NOTE: Ideally 0, typically 0.5V/µsecs.

vii) Infinite Power supply rejection ratio(PSRR)

The ratio of change in output voltage to change in supply voltage(due to ac ripples) is called the Power supply rejection ratio.

$$\text{i. e,} PSRR = \frac{\Delta V_{out}}{\Delta V_{in}}$$

NOTE: Ideally ∞,, typically 50-100dB

viii) Input Bias Currents:

The current flowing through the base terminals of the input stage transistors circuit of an op-amp is called input bias currents, denoted as I_{B1} and I_{B2}.

NOTE: Ideally 0A, typically 80nA and maximum 500nA.

ix) Input offset current:

The magnitude of the difference between the input bias currents is called Input offset current, denoted as I_{io}.

i.e., $I_{io} = |I_{B2} - I_{B1}|$

NOTE: Ideally 0A, typically 20nA, and maximum 200nA.

x) Input offset voltage:

Op-amp produces zero output voltage for zero input voltage, but practically a small dc voltage appears across the output terminal of an op-amp even if the input is zero, that voltage is called input offset voltage, denoted as V_{io}.

NOTE: Ideally 0V, typically 1mV, and maximum 5mV.

NOTE: The typical values given in the above characteristics are related to μA741.

1.5. Concept of Virtual ground

Op-amp is a differential amplifier, which amplifies the difference between the two input signals.

$$\text{i.e., } V_{out} = A(V_2 - V_1)$$

We know that, the ideally A=∞.

$$\text{Therefore, } V_{non-inv} - V_{inv} = 0$$

or

$$V_{non-inv} = V_{inv}$$

From the above equation, observed that the inverting terminal voltage is the same as the non-inverting terminal voltage. i.e., if one of the input terminals is connected to ground(zero potential), the other terminal voltage is also zero, which indicates that there are virtually short-circuited. In other words, a node that has zero potential with respect to the ground but is not connected to the ground. This concept is called virtual ground.

1.6. Applications of Op-amps

In this section, the linear applications of op-amp have been discussed.

1.6.1. Inverting amplifier

An electronic circuit or device, which increases the strength of the input signal and the output signal is 180° out phase with the input signal is called inverting amplifier. Figure(3) shows the circuit diagram of the op-amp inverting amplifier.

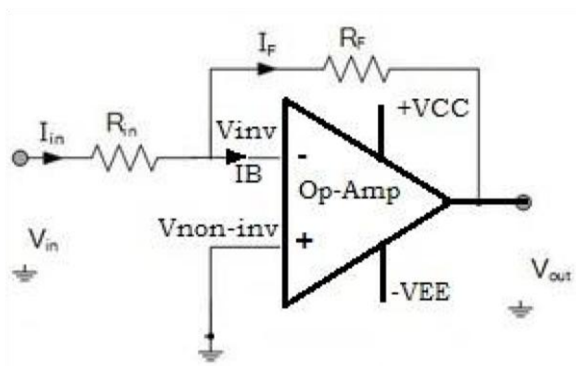


Figure 3: Op-amp Inverting amplifier circuit

The input signal is applied to the inverting terminal through R1 and the non-inverting terminal is connected to the ground, RF is the feedback(Negative feedback) resistor connected from the output terminal to the input terminal. Applying KCL at inverting node,

$$I_{in} = I_B + I_F \text{ ------------ } (1)$$

W.K.T., $I_B = 0$, Therefore

$$I_{in} = I_F \text{ ------- } (2)$$

$$\frac{V_{in} - V_{inv}}{R_{in}} = \frac{V_{inv} - V_{out}}{R_F} \text{ ----- } (3)$$

$V_{non-inv} = 0$, therefore $V_{inv} = 0$, since Virtual ground

Therefore, or

$$\frac{V_{in}}{R_{in}} = -\frac{V_{out}}{R_F} ---------(4)$$

$$V_{out} = -V_{in}\left(\frac{R_F}{R_{in}}\right) ------(5)$$

From equation (5), it has been observed that the output signal is R_F/R_{in} times that of the input signal with a negative sign indicates phase reversal.

$$\text{i.e., Gain } (A_v) = \frac{R_F}{R_{in}} \text{ - - - - - (6)}$$

1.6.2. Non-Inverting amplifier

An electronic circuit or device, which increases the strength of the input signal and the output signal is in phase with the input signal is called a non-inverting amplifier. Figure(4) shows the circuit diagram of the op-amp non-inverting amplifier.

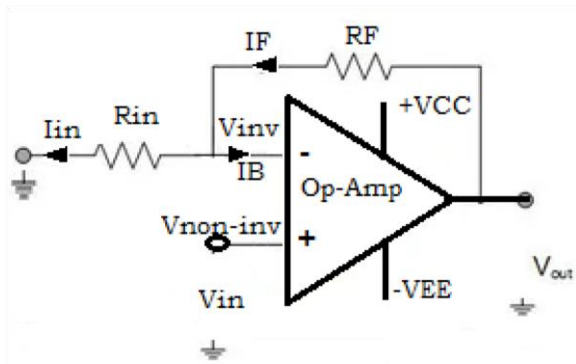


Figure 4: Op-amp Non-Inverting amplifier circuit

The input signal is applied to the non-inverting terminal and the non-inverting terminal is connected to the ground through R1, RF is the feedback(Negative feedback) resistor connected from the output terminal to the input terminal.

Applying KCL at inverting node,

$$I_F = I_B + I_{in} \text{ - - - - - - - - - - - - (7)}$$

W.K.T., $I_B = 0$, Therefore

$$I_{in} = I_F \text{ - - - - - - - - (8)}$$

$$\frac{V_{inv} - 0}{R_{in}} = \frac{V_{out} - V_{inv}}{R_F} \text{ - - - - - - (9)}$$

$V_{non-inv} = V_{in}$, therefore $V_{inv} = V_{in}$, since Virtual ground

Therefore,

$$\frac{V_{in}}{R_{in}} = \frac{V_{out} - V_{in}}{R_F} \text{ - - - - - - - - -(10)}$$

$$V_{out} = +V_{in}\left(1 + \frac{R_F}{R_{in}}\right) \text{ - - - - - - -(11)}$$

From equation (11), it has been observed that the output signal is $1+R_F/R_{in}$ times that of the input signal with a positive sign indicates the output is in-phase with the input signal.

$$\text{i.e., Gain } (A_v) = 1 + \frac{R_F}{R_{in}} - - - - - (12)$$

1.6.3. Op-Amp summing amplifier

An electronic circuit or device, which amplifies the summation of two or more signals is called a summing amplifier. Figure(5) shows the circuit diagram of the op-amp summing amplifier for three inputs.

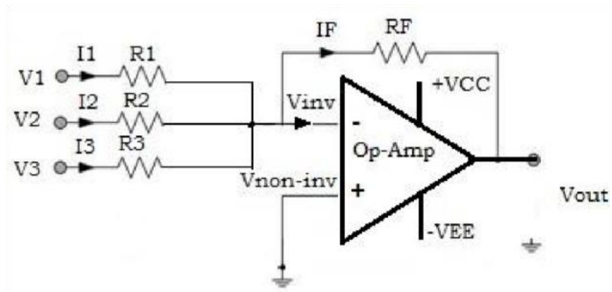


Figure 5: Op-amp summing amplifier circuit.

Input signals are applied to the inverting terminal through R1, R2, and R3, and the non-inverting terminal is connected to the ground, RF is the feedback(Negative feedback) resistor connected from the output terminal to the input terminal.

Applying KCL at inverting node,

$$I_1 + I_2 + I_3 = I_B + I_F - - - - - - - - - - - - (13)$$

W.K.T., $I_B = 0$, Therefore

$$I_1 + I_2 + I_3 = I_F - - - - - - - - (14)$$

$$\frac{V_1 - V_{inv}}{R_1} + \frac{V_2 - V_{inv}}{R_2} + \frac{V_3 - V_{inv}}{R_3} = \frac{V_{inv} - V_{out}}{R_F} - - - - - - (15)$$

$V_{non-inv} = 0$, therefore $V_{inv} = 0$, since Virtual ground

Therefore, or

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = -\frac{V_{out}}{R_F} - - - - - - - - -(16)$$

$$V_{out} = -(V_1 (\frac{R_F}{R_1}) + V_2 (\frac{R_F}{R_2}) + V_3 (\frac{R_F}{R_3})) - - - - - -(17)$$

if $R_F=R_1=R_2=R_3$,

$$V_{out} = -(V_1 + V_2 + V_3) ------(18)$$

From equation (18), it has been observed that the output signal is the negative sum of the input signals.

1.6.4. Op-Amp Difference amplifier

An electronic circuit or device, which amplifies the difference of two signals is called a difference amplifier and also called op-amp subtractor. Figure(6) shows the circuit diagram of the op-amp subtractor amplifier.

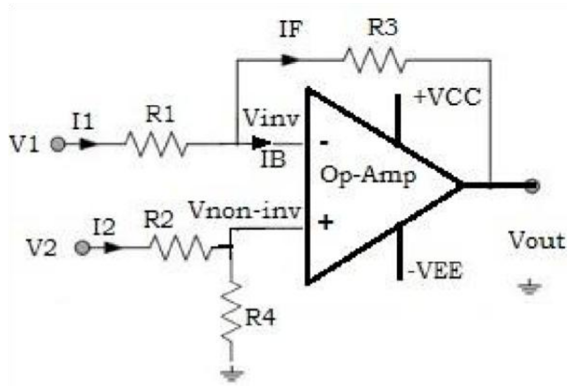


Figure 6: Op-amp Difference amplifier circuit.

Input signals are applied to the inverting terminal through R1, and the non-inverting terminal through R2, RF is the feedback(Negative feedback) resistor connected from the output terminal to the input terminal.

At inverting node,

$$I_1 = I_F \;-\,-\,-\,-\,-\,-\,-\,- (19)$$

$$\frac{V_1 - V_{inv}}{R_1} = \frac{(V_{inv} - V_{out})}{R_3} \;-\,-\,-\,-\,-\,-\,-\,-\,- (20)$$

At the non-inverting node,

$$V_{non-inv} = I_2 R_4 \;-\,-\,-\,-\,-\,-\,-\,- (21)$$

$$V_{non-inv} = V_2 \left(\frac{R_4}{R_2 + R_4}\right) \;-\,-\,-\,- (22)$$

$V_{non-inv} = V_{inv}$, since Virtual ground

Determining V_{out} using superposition principle.

if V2=0;

$$V_{out} = -V_1 \left(\frac{R_3}{R_1}\right) \;-\,-\,-\,-\,-\,-\,-\,- (23)$$

if V1=0;

$$V_{out} = V_2 \left(\frac{R_4}{R_2+R_4}\right)\left(\frac{R_1+R_3}{R_1}\right) \;-\,-\,-\,-\,- (24)$$ (Since, Non-inverting amplifier)

therefore,

$$V_{out} == -V_1 \left(\frac{R_3}{R_1}\right) + V_2 \left(\frac{R_4}{R_2+R_4}\right)\left(\frac{R_1+R_3}{R_1}\right) \;-\,-\,-\,-\,- (25)$$

if $R_1 = R_2 = R_3 = R_4$

$$V_{out} = -V_1 + V_2 \;-\,-\,-\,-\,- (26)$$

From equation (18), it has been observed that the output signal is the difference between the two input signals.

1.6.5. Op-Amp Voltage follower

In an electronic circuit or device, the output signal is same as the input signal or output follows the input, such circuit is called voltage follower. The voltage follower circuit acts as a buffer. Figure(7) shows the circuit diagram of the op-amp voltage follower.

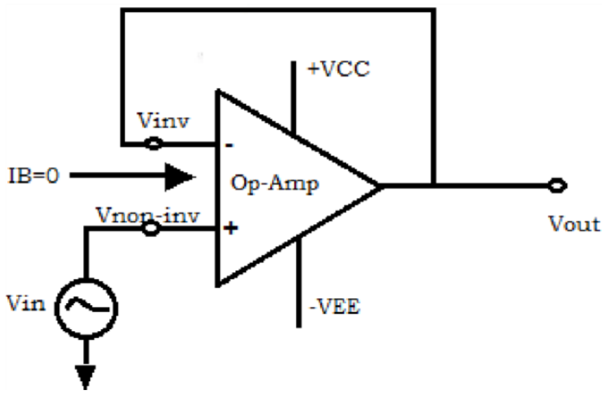


Figure 7: Op-amp voltage follower circuit.

Input signals are applied to the non-inverting terminal short-circuited the output terminal with the inverting terminal(feedback).

From the circuit,

$$V_{non-inv} = V_{in} - - - - - (27)$$

$$V_{inv} = V_{non-inv} = V_{in} - - - - - - - - (28)$$ and

$$V_{out} = V_{inv} - - - - - - - - - - (29)$$

Therefore,

$$V_{out} = V_{in} - - - - - - (30)$$

Equation (30) shows that the output signal is equal to the input signal.

1.6.6. Op-Amp Integrator

An electronic circuit or device, which performs the integration of the input signal, is called an Integrator. Figure(8) shows the circuit diagram of the op-amp Integrator.

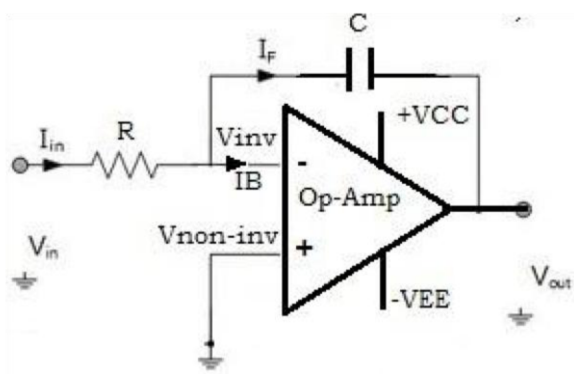


Figure 8: Op-amp Integrator circuit.

The input signal is applied to the inverting terminal through a resistor R and Capacitor C(Feedback element) is connected from the output terminal to inverting input terminal.

From the circuit,

$$I_{in} = I_F - - - - - (31)$$

$$\frac{(V_{in} - V_{inv})}{R} = C\frac{d}{dt}(V_{inv} - V_{out}) - - - - - - - - (32)$$

We know that

$$V_{non-inv} = V_{inv} = 0 - - - - - (33)$$

(Since, Virtual Ground)

Therefore,

$$\frac{V_{in}}{R} = C\frac{d}{dt}(-V_{out}) - - - - - - - - (34)$$

Integrating on both sides, we get

$$\int \frac{V_{in}}{R} dt = C\int \frac{d}{dt}(-V_{out})dt - - - - - - - - (35)$$

$$V_{out} = -\frac{1}{RC}\int V_{in}dt - - - - - - - - -(36)$$

Equation (36) shows that the output signal is equal to the integral of the input signal.

1.6.6. Op-Amp Differentiator

An electronic circuit or device, which performs the Differentiation of the input signal, is called a Differentiator. Figure(9) shows the circuit diagram of the op-amp differentiator.

$$f = \frac{1}{2\pi RC}$$

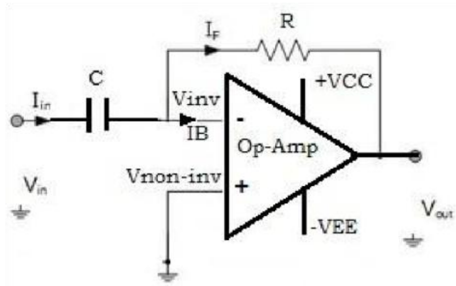


Figure 9: Op-amp differentiator circuit.

The input signal is applied to the inverting terminal through a resistor C and Resistor R (Feedback element) is connected from the output terminal to inverting input terminal.

From the circuit,

$$I_{in} = I_F - - - - - (37)$$

$$C\frac{d}{dt}(V_{in} - V_{inv}) = \frac{(V_{inv} - V_{out})}{R} - - - - - - - - (32)$$

We know that

$$V_{non-inv} = V_{inv} = 0 - - - - - (38)$$

(Since, Virtual Ground) Therefore, $C\frac{d}{dt}V_{in} = -\frac{V_{out}}{R} - - - - - - - - (39)$

or

$$V_{out} = -RC\frac{d}{dt}V_{in} - - - - - - - - - (40)$$

Equation (40) shows that the output signal is equal to the derivative of the input signal.