UNIT 8 APPLICATIONS OF OPERATIONAL AMPLIFIERS

Structure

8.1 INTRODUCTION

The infinite open loop gain, A_{OL} of an ideal op amp or as high A_{OL} as 200,000 for realistic op amp 741C is of no use for most applications in which op amp can be used. The open loop gain is also not a constant. It varies with changes in the temperature, power supplied, and manufacturing techniques. With such a large gain, the output corresponding to a small input voltage gets clipped to $+V_{SAT}$ or $-V_{SAT}$. Moreover for output voltages within the saturation voltages, the input voltages, have to be of the order of a few microvolts. Such low voltages are difficult to obtain even in laboratories. Since in linear amplifiers the output voltage is proportional to the input voltage, therefore the open loop operational amplifiers cannot be used. However, in certain applications like comparators (already discussed in Unit 9) and square wave generators open loop amplifiers are used.

In order for using the op amp in linear amplifiers and most other applications, it is essential to design some external circuit. Such a circuit is made using the concept of negative feedback which will be discussed later in section 8.7. In this application based Unit, unless stated otherwise, we shall use op amp 741C. The output pin is connected to the inverting input pin 2 using a resistor. It can be shown that the gain of such an amplifier with negative feedback, which is known as the closed loop gain, A_{OL} is totally independent of the open loop gain, A_{OL} of the op amp and depends only upon external circuit parameters.

Objectives

After studying this unit, you should be able to:

- draw the circuit diagram for the inverting amplifier and find out its closed loop gain, A_{CL},
- use an inverting amplifier as a multiplier or divider,
- design an inverting amplifier with a particular gain,
- draw a circuit diagram for a non-inverting amplifier and find out its closed loop gain,
- draw a circuit diagram for an inverting adder and use this circuit for a channel amplifier,

- draw the circuit diagram for a basic differentiator and show that the output of such a circuit is the derivative of the input waveform,
- draw the circuit diagram for a basic integrator and show that the output of such a circuit is the integral of the input waveform,
- explain the concept of feedback in amplifiers.

8.2 INVERTING AMPLIFIER

Introduction

Consider the circuit given in the Fig.8.1. In this circuit the output pin 6 is connected through a resistor R_F to the inverting input pin 2. The input voltage is given to pin 2 through an input resistor R_I. The inverting input pin 3 is grounded. The output pin 6 is also grounded through a resistor R_L. In this circuit, two realistic but very simplifying assumptions are made which are as follows. If the output voltages is not in saturation then the differential input is zero and the current entering into inverting and non-inverting input pins is negligible.

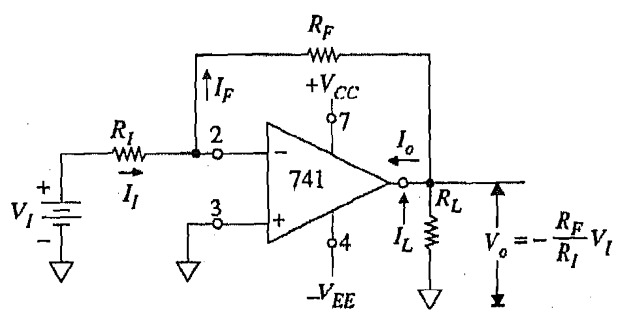


Fig.8.1: Inverting amplifier.

Positive input

A positive input voltage ($+V_I$) is applied to the inverting (–) input pin 2 through input resistor R_I and the feedback resistor R_F provides tho necessary feedback from the output to the input. As per the realistic assumptions made above, no current is entering into the op amp through pin 2. And because non-inverting (+) input pin 3 is grounded, therefore pin 2 is also at ground voltage, i.e. 0V. Thus though the pin 2 is not connected to the ground, yet it virtually appears to be grounded. It should be noted that in the equivalent circuit of an op amp (Fig.7.9) pins 2 and 3 are connected to each other through a very high resistance (ideally infinite). We, therefore, say that pin 2 or the inverting input is at virtual ground.

In the circuit of Fig.8.1, the current through R_I is decided by the voltage drop across it. One end of R_I is connected to $+V_I$ and another end is at 0V. Therefore, the voltage drop across R_I is $+V_I$. The input current, I_I, flowing through R_I from a point of higher potential to a point of lower potential (i.e. pin 2 which is at 0V) is

$$I_I = \frac{V_I}{R_I} \tag{8.1}$$

Since the current docs not enter the op amp, therefore I_I has to flow through R_F. Therefore, I_F the current flowing through R_F is equal to I_I. That is $I = I_I = I_F$. Thus the voltage drop across R_F is

$$V_F = IR_F \tag{8.2}$$

Putting for I from Eq, (8.1) we get

$$V_F = \frac{V_I}{R_I} R_F \quad (8.3)$$

Since pin 2 is at virtual ground, R_L is in parallel with R_F. Therefore, the magnitude of V_F is equal to V_O. But V_F is negative because the current flows from pin 2 (which is at 0V) to pin 6. Thus, V_O the voltage between pin 6 and ground is

$$V_O = -V_F$$

$$= -\frac{V_I}{R_I} R_F = -\frac{R_F}{R_I} V_I \quad \text{(using Eq. 8.3)}$$

The closed loop gain of the amplifier, A_{CL}, is

$$A_{CL} = \frac{V_O}{V_I} = -\frac{R_F}{R_I} \quad (8.4)$$

Thus A_{CL} depends on R_F and R_I only and does not at all depends on the open loop gain operational amplifier. Since A_{CL} is negative, that is may we call this co guration of the amplifier as inverting amplifier. The choice of R_F and R_I is in the hands of the designer and the gain of practically any value can be obtained. In all practical applications the value of R_I should be chosen to be large, say 10 kΩ, so that it does not short out the input resistance of the op amp.

The output current I_O is the sum of the current I flowing through R_I and the current $I_L = V_O/R_L$ flowing through the load R_L. Thus

$$I_O = I + I_L \quad (8.5)$$

While designing an op amp based amplifier, the mount of current required at the output should also bo kept in mind. The value of I is set by V_I and R_I which are in turn set by the design requirement. Thus, tho output current I_O is controlled by proper choice of R_L.

The inverting amplifier circuit can be used for multiplication and division. The output voltage is R_F/R_I times the input voltage. If tho input voltage represents some number then tho output voltage will be equal to that number multiplied by the factor R_F/R_I. Tho ratio R_F/R_I is under the control of tho user and can assume any value. By making R_I greater than R_F, the inverting amplifier can be used for division.

Example:

Design an amplifier using op amp 741C and V_I of 1V for a gain of –8 and with I_O of 0,9 mA.

Solution:

Choose R_I = 10 kΩ.

with $A_{CL} = -8$, $R_F = -8R_I = 80$ kΩ.

Using equation (8.1)

$$I = \frac{V_I}{R_I} = \frac{1V}{10\,k\Omega} = 0.1\,mA$$

From equation (8.5),

$$I_L = I_O - I = 0.9\,mA - 0.1\,mA = 0.8\,mA$$

$$V_O = 1V_O \times (-8) = -8V$$

$$I_L = \frac{V_O}{R_L}$$

Or $$R_L = \frac{V_O}{V_D} = \frac{8V}{0.8\,mA} \; 10\,k\Omega.$$

Hence, for the required design R_I = 10 kΩ and R_F = 80 kΩ and R_L = 10 kΩ. The dc bias for the op amp should be well above the expected output. In this example V_O is –8V, therefore a ±9V power supply will not be a good choice, for –8V would be just equal to $-V_{SAT}$. Therefore, a greater value of power supply is chosen, ±10V or above.

SAQ 1

What is the output voltage in the circuit given below?

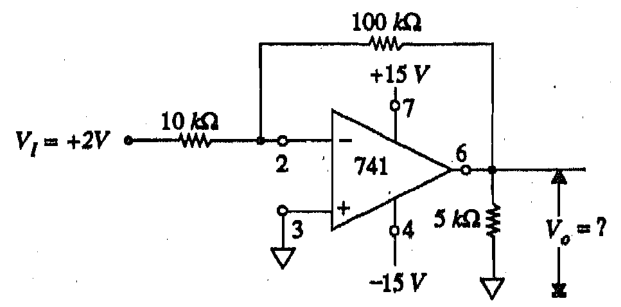


Fig.

8.3 NON-INVERTING AMPLIFIER

The circuit given in Fig.8.2 in for a non-inverting amplifier. In thin circuit R_I continue to bo connected as in the case of inverting amplifier except that the R_I is ground as shown and tho input voltage V_I is given to the non-inverting (+) input pin 3,

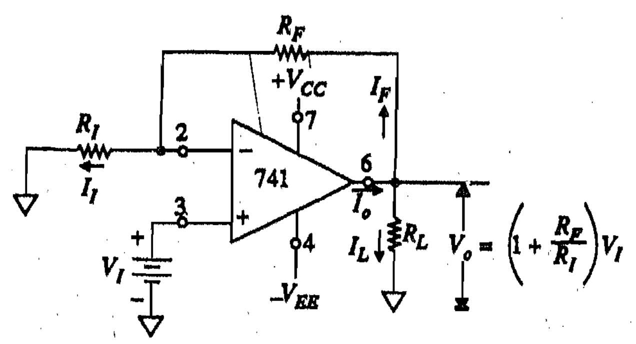


Fig.8.2: Nan-Inverting amplifier.

For the reasons discussed in the previous section, tho inverting input pin 2 is also at the same voltage at which non-inverting input pin 3 in. Thus, the pin 2 is at $+V_I$, which sets the current I_I through R_I. Tho voltage drop across R_I being V_I, we got

$$I_I = \frac{V_I}{R_I} \tag{8.6}$$

Obviously, I_I flows from pin 2 to the ground. For the same reasons, I_F tho current flowing through R_F has to be equal to I_I, i.e. $I = I_I = I$, Thus, the current I flows from output terminal pin 6 to pin 2 to ground. Hence, the output pin 6 is at a greater potential than pin 2. Since the load resistor R_L is now in parallel with tho series combination of R_I and R_F therefore the output voltage is equal to the sum of voltage across R_I and R_F. Thus

$$V_O = V_I + IR_F$$

$$= V_I + \frac{V_I}{R_I} R_F \quad \text{(using Eq. 8.6)}$$

$$= V_I(1 + \frac{R_F}{R_I})$$

Or the closed loop gain of the amplifier is

$$A_{CL} = \frac{V_O}{V_I} = (1 + \frac{R_F}{R_I}) \tag{8.7}$$

Notice that A_{CL} has the same sign as the input voltage V_I i.e. positive. For this reason, we call such an amplifier to be a non-inverting amplifier. Notice further that in this case also the gain depends upon the values of R_F and R_I and not on the parameters of the operational amplifier. However, the gain is always greater than unity. The ratio R_F/R_I can be made as small as possible and the gain can be made close to unity, but it can never be less than unity. Pin 6 being at a potential greater than the ground potential, therefore the load current I_L flows from pin 6 to ground through the load resistor R_L.

Example:

Design an amplifier using op amp 741C and V_I of 0.2V for a gain of +10 with I_O of 0.1 mA.

Solution:

Choose $R_I = 10$ kΩ.

Given $A_{CL} = +10 = 1 + (R_F/R_I)$

or $\quad R_F/R_I = 10 - 1 = 9$

or $\quad R_F = 9R_I = 90$ kΩ

$I = V_I/R_I = 0.2\text{V}/10 \text{ k}\Omega = 0.02$ mA.

$V_O = +10V_I = 10 \times 0.2\text{V} = 2\text{V}$

From $I_O = I + I_L$ we get

or $\quad I_O = 0.02 + V_O/R_L = 0.1$ mA

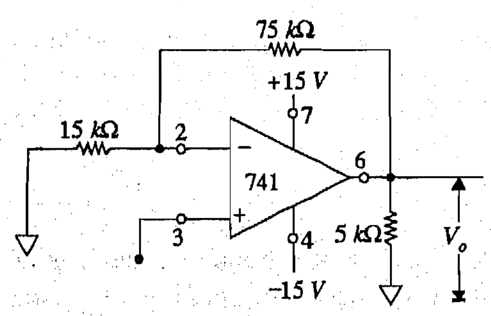
or $\quad V_O/R_L = (0.1 - 0.02)\text{mA} = 0.08$ mA

or $\quad R_L = 2\text{V}/0.08 \text{ mA} = 25$ kΩ.

Hence, for the required design $R_I = 10$ kΩ, $R_F = 90$ kΩ and $R_I = 25$ kΩ.

SAQ 2

What is the gain of the amplifier shown in the figure given below?



8.4 INVERTING ADDER

The inverting amplifier configuration of the op amp is useful in many applications. **The** inverting amplifier can be used for multiplication and division as stated in **section** 8.2. The circuit of Fig.8.1 has only one input through R_I. The **number** of inputs can be increased to any number. Consider the circuit given in Fig.8.3 in which **there** are three resistors as input resistors connected to pin 2 and a common R_F for **all** the R_I**'s**. Since the pin 3 is grounded, pin 2 is at OV.

The current flowing through R_F is the sum of all the currents **reaching** summing point **S at** pin 2. These current are set by V_{I1} and R_{I1} V_{I2} and R_{I2} and V_{I3} and R_{I3}. Therefore,

$$I_F = I_{I1} + I_{I2} + I_{I3}$$

$$= \frac{V_{I1}}{R_{I1}} + \frac{V_{I2}}{R_{I2}} + \frac{V_{I3}}{R_{I3}}$$

The output voltage V_O is

$$V_O = -I_F \cdot R_F$$

$$= -\left(\frac{V_{I1}}{R_{I1}} + \frac{V_{I2}}{R_{I2}} + \frac{V_{I3}}{R_{I3}}\right) R_F \qquad (8.8)$$

And if all the resistors are of same value, **i.e** R = $R_F = R_{I1} = R_{I2} = R_{I3}$ **then** we get

$$V_O = -(V_{I1} + V_{I2} + V_{I3}) \qquad (8.9)$$

Thus the output of this circuit is the sum of all the input voltages. This circuit is **known** as inverting adder. The negative sign indicates **180°** phase change between **the** input and the output.

If all the R_I**'s** are chosen to be same and R_F **is of** different value then the output voltage will be

$$V_O = -(V_{I1} + V_{I2} + V_{I3}) \qquad (8.10)$$

This equation indicates that the sum of the input is multiplied by a factor R_F/R_I which is under the control of the user. In this equation if R_F/R_I **is** made equal to **1/3,** then the resulting amplifier is averaging amplifier.

The circuit of Fig.8.3 has several applications. Apart from the applications mentioned above if the circuit is made with different values **of** R_I**'s** as shown, then **Eq.8.8** suggests that the output voltage is the sum of **all** the outputs corresponding to each input. Such a circuit is also used in digital to analog conversion (which will be discussed in Unit **12,** Block 4). Alternatively, all the inputs need not be used. **Only** one may be used at a time. In that situation, this circuit is being used for different gains set by **different** R_I**'s**. Such a circuit can be used as a **channel** amplifier.

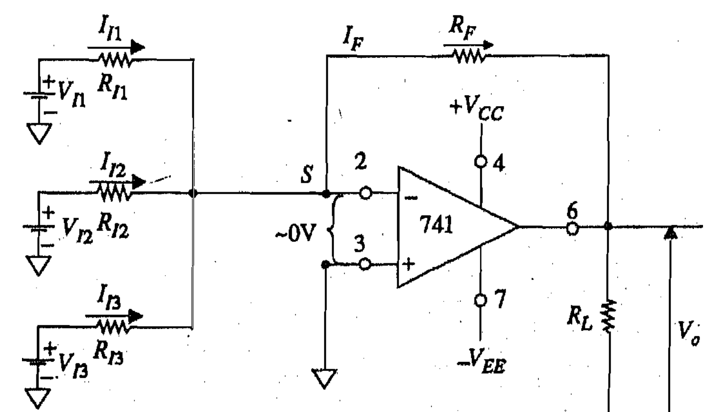


Fig.8.3: Inverting adder.

Example:

Design a 4-channel inverting amplifier using op amp 741C with gains –20, –15, –10, and –5.

Solution:

Make a 4-input inverting amplifier circuit as shown in Fig.8.4. The Eq.8.8 is rewritten for four inputs as follows

$$V_O = -\left(\frac{V_{I1}}{R_{I1}} + \frac{V_{I2}}{R_{I2}} + \frac{V_{I3}}{R_{I3}} + \frac{V_{I4}}{R_{I4}}\right) R_F$$

$$= -\left(V_{I1}\frac{R_F}{R_{I1}} + V_{I2}\frac{R_F}{R_{I2}} + V_{I3}\frac{R_F}{R_{I3}} + V_{I4}\frac{R_F}{R_{I4}}\right) \qquad (8.11)$$

It is clear that the gain of each channel can be changed independently by changing the input resistor. We have

$$A„ = \frac{R_F}{R_{I1}},\ A_{CL2} = \frac{R_F}{R_{I2}}\ A_{CL3} = \frac{R_F}{R_A},\ A_{CL4} = \frac{R_F}{R_{I4}}$$

Choose the value of R_I equal to 10 kΩ for tha channel with the highest gain, i.e –20 in this example. Find out the value of R_F as

$$A„ = -20 = \frac{R_F}{R_{I1}} = \frac{R_F}{10\ \text{k}\Omega}$$

Fig.8.4: Four-input inverting amplifier.

Thus R_F = 20 x 10 = 200 kΩ. With the thus obtained value of R_F find the values of R_I's for other channels.

For channel 2, $A_{CL2} = -15 = 200/R_{I2}$

or R_{I2} = 200/15 = 13.33 kΩ

For channel 3, $A_{CL3} = -10 = 200/R_{I3}$

or R_{I3} = 200/10 = 20 kΩ

For channel 4, $A_{CL4} = -3 = 200/R_{I4}$

or R_{I4} = 200/5 = 40 kΩ.

The design result can be summarised as follows

$R_F = 200\text{k}\Omega$

Channel	A_{CL}	R_I
1	−20	10 kΩ
2	-15	13.33 kΩ
3	−10	20 kΩ
4	-5	40162

SAQ 3

What is the output of the circuit given below?

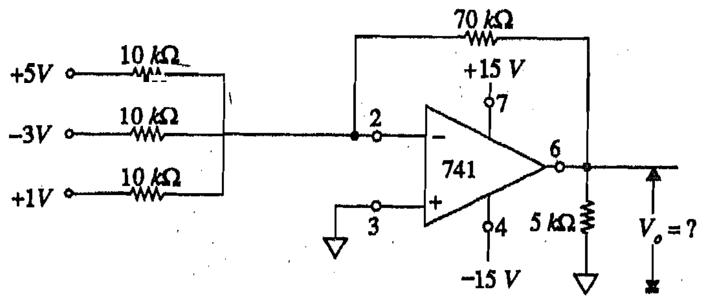


Fig.

8.5 BASIC DIFFERENTIATOR

Fig.(8.5) shows the circuit for basic differentiator which performs tho mathematical operation of differentiation. The output waveform is the derivative of the input waveform. The differentiator circuit is obtained by replacing R_I of an inverting amplifier by a capacitor, while rest of the circuit remains the same. For the reasons discussed in the case of inverting amplifier, the current I_C flowing through tho capacitor C should be equal to the current I' flowing through the resistor R_F. Thus

$$I_C = I_F$$

The current I_C flows from tho generator to pin 2 from where it flows through R_F. The pin 2 being at 0V, the voltage drop across C is V' and tho drop across R_F is $-V_O$. Recall that tho currant flowing through a capacitor C is C times the rate of change of voltage across the capacitor, Therefore

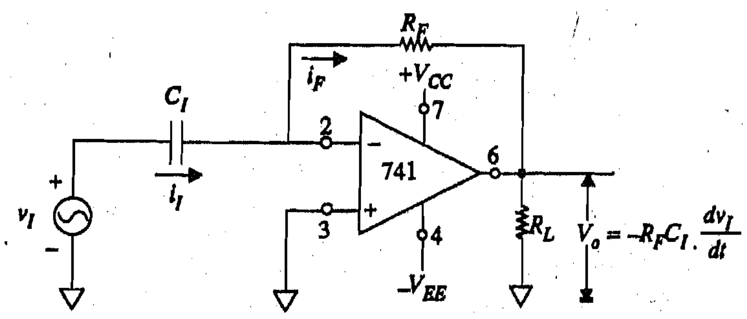


Fig.8.5: Basic differentiator.

$$I_C = C_I \frac{dV_I}{dt}$$

and
$$I_F = -\frac{V_O}{R_F}$$

Thus we get

$$C_I \frac{dV_I}{dt} = -\frac{V_O}{R_F}$$

Rearranging, we get

$$V_O = -R_F C_I \frac{dV_I}{dt}$$

If the product $R_F C_I = 1$, then

$$V_O = -\frac{dV_I}{dt} \qquad (8.12)$$

Thus the output voltage is the negative derivative of the input voltage V_I. If the input waveform is a sine wave, then the output waveform will be a cosine wave. And if the input waveform is a square wave, then the output waveform will be a spike wave from as shown in the Fig.8.6.

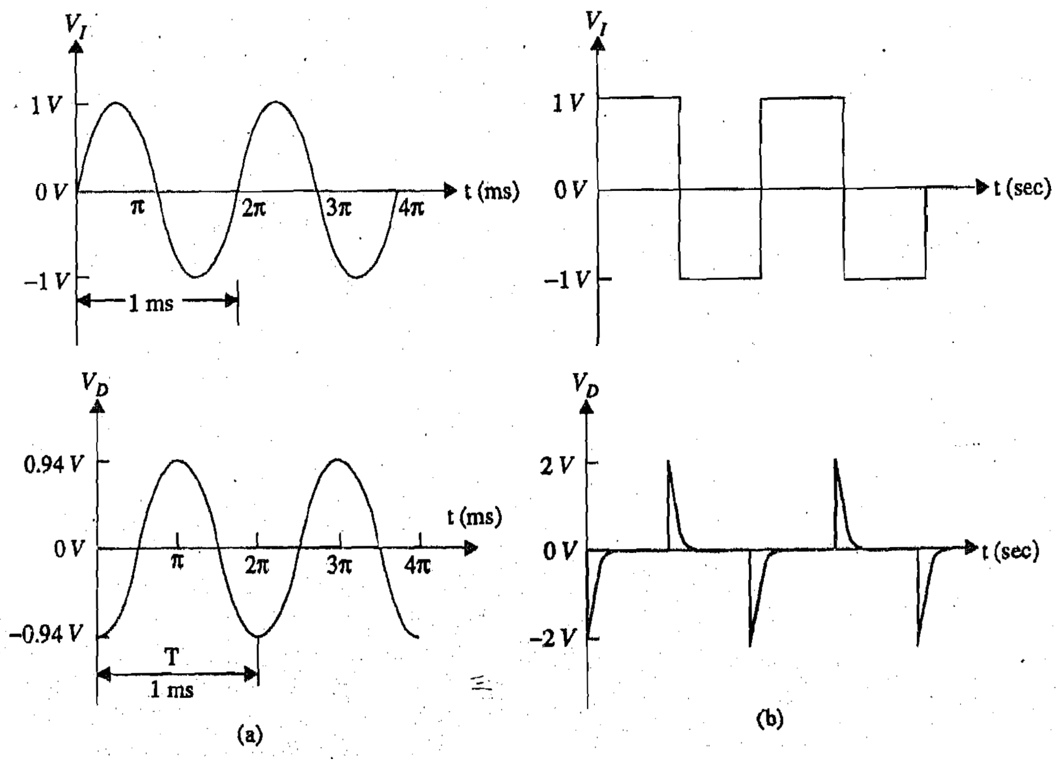
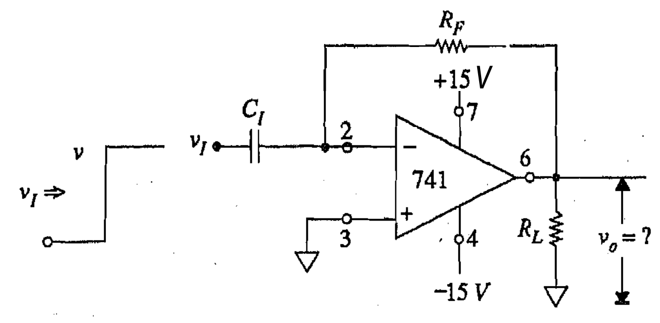


Fig.8.6: Output of a basic differentiator when input is (a) sine wave and (b) square wave.

SAQ 4

Find the output waveform for the basic differentiator shown below.



8.6 BASIC INTEGRATOR

Fig.(8.7) shows the circuit for a basic integrator which performs the mathematical operation of integration. The output waveform, V_O, is the integral of the input waveform, V_I. The integrator circuit is obtained by replacing the resistor R_F by a capacitor C_F in the circuit of inverting amplifier, while rest of the circuit remaining same. For the reasons stated in the case of inverting amplifier, the current I_I flowing through the resistor R_I has to be equal to the current I_F flowing through the capacitor C_F. Thus

$$I_I = I_F$$

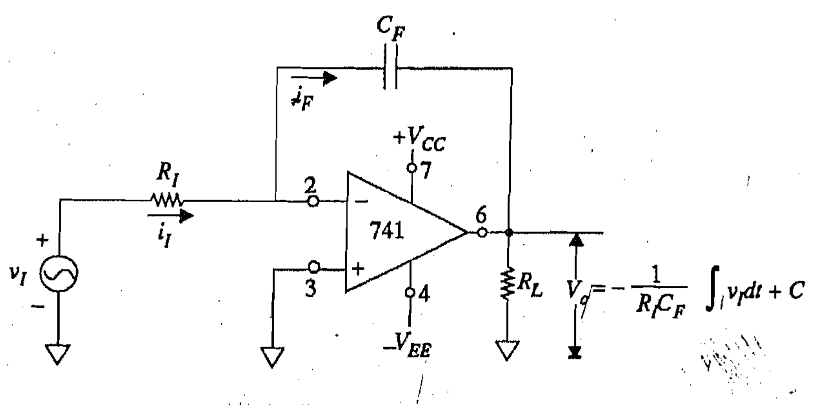


Fig.8.7: Basic integrator.

The current I_I flows from the generator to pin 2 and from it flows through the capacitor C_F. The pin 2 being at OV, the voltage drop across $R_I = V_I$ and that across C_F is $-V_O$. Therefore,

$$I_I = \frac{V_I}{R_I}$$

and $$I_F = C_F \frac{d(-V_O)}{dt}$$

Thus $$\frac{V_I}{R_I} = C_F \frac{d(-V_O)}{dt}$$

or $$\frac{V_I}{R_I}\, dt = C_F \frac{d}{dt}\,(-V_O)\, dt$$

$$= C_F\,(-V_O) + \text{constant of integration}$$

or $$V_O = -\frac{1}{R_I C_F}\; V_I\, dt + \text{constant of integration} \qquad (8.13)$$

The constant of integration is proportional to the value of V_O at **time** t = 0. The **Eq.(8.13)** shows that the output is directly proportional to the integral of the input voltage waveform. If the product $R_I C_F$ **is** made equal to 1 and constant of integration is 0, then **we** get

$$V_O = -\,V_I dt \qquad \textbf{(8.14)}$$

If the input waveform is **sine** wave then the output waveform is cosine wave. And if the input **waveform** is a square wave, then the output waveform is a triangular wave as shown in Fig.8.8.

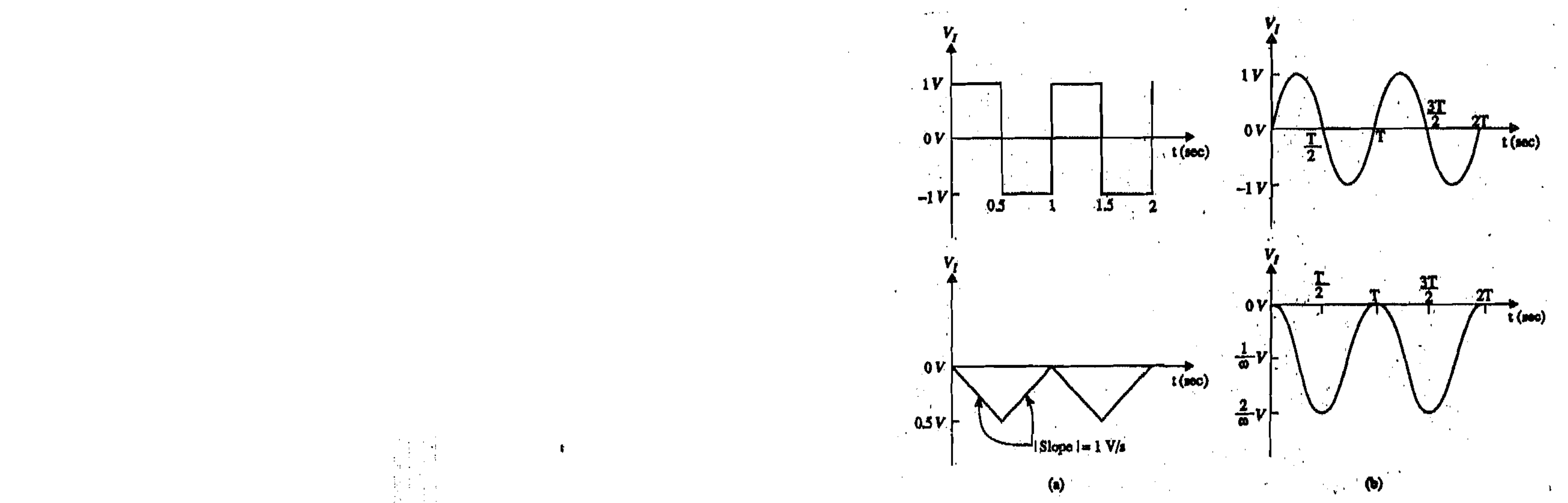
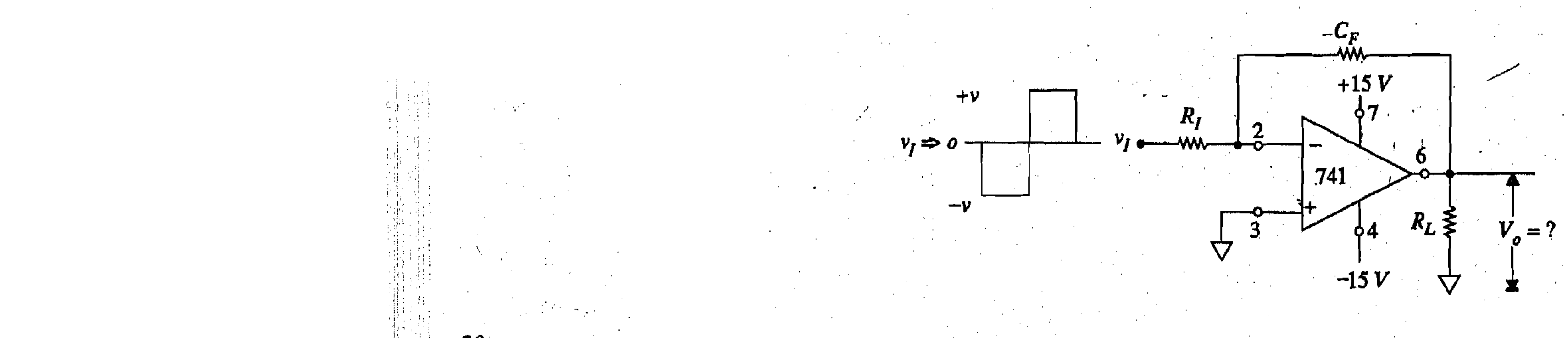


Fig.8.8: Output of a basic Integrator when input is (a) **square wave.** (b) **sine wave and**

SAQ 5

Trace the output **waveform** for tho **basic** integrator shown below.



8.7 FEEDBACK IN OP AMP

In the beginning of this unit, two simplifying assumptions were made. Consequently, it was practically taken that no current enters the pin 2 and the current flowing through R_I has to be equal to that flowing through R_F. The pins 2 and 3 were also taken at the same potential. This made the derivations to be quite simplistic. However, the situation is not so. Some current, howsoever small, enters the op amp giving rise to some voltage drop across the input. A mention was made about the negative feedback, but it was not described. Let us see whether the realistic analysis of the circuits used above leads to the same results. The closed loop amplifiers considered above have all been negative feedback amplifiers.

In an amplifier with feedback, there are two basic networks. One is the amplifier and another is feedback network which feeds back a part of the output voltage to the input. If the feedback voltage adds to the input voltage, then the feedback is known as positive feedback. Positive feedback increase the gain. If the feedback voltage is such that it decreases the input voltage, then the feedback is known as the negative feedback, Negative feedback decreases the gain. A description of advantages and disadvantages of negative and positive feedback is beyond the scope of this unit. Therefore, this aspect will not be considered here,

Consider the circuit shown in Fig.8.9. The output terminals are connected to the feedback network and the output of the feedback network is connected in series with the input voltage source. Thus the input voltage V_I in this configuration goes to the non-inverting input pin 3 and the feedback voltage V_F goes to the inverting input pin 2.

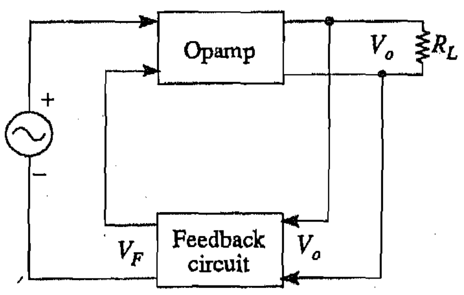


Fig.8.9: Feedback in op amp.

Let us consider the non-inverting circuit of **Fig.8.2** which is redrawn here as shown in **Fig.8.10**. Comparing this circuit with that of **Fig.8.9**, we find that R_I and R_F form a feedback network. The output voltage V_O is dropped across the series combination of R_I and R_F. The voltage drop across R_I is the feedback voltage V_F and is applied to the inverting input pin 2. The input voltage V_I is applied to the non-inverting input pin 3.

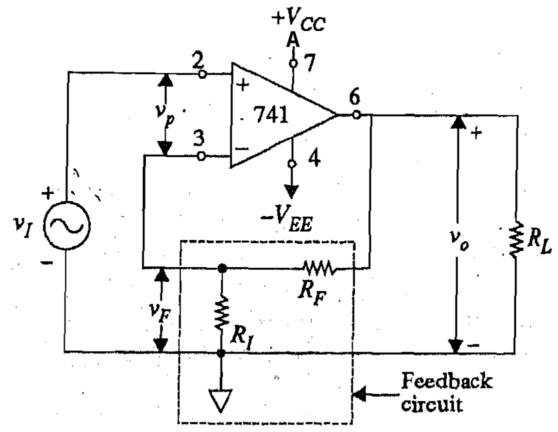


Fig.8.10: Non-inverting amplifier circuit of **Fig.8.2 redrawn.**

Recall that the closed loop gain A_{CL} is defined as

$$A_{CL} = \frac{V_O}{V_I}$$

The output voltage V_O, in the circuit of **Fig.8.10** is

$$V_O = A_{CL} (V_1 - V_2) \quad (8.15)$$

where V_I is the input voltage V, and V_2 is the feedback voltage V_F. Thus considering division of V_O by the feedback network across R_I and R_F, we get

$$V_2 = V_F$$

$$= \frac{R_I V_O}{R_I + R_F} \quad (8.16)$$

Putting for V_1 and V_2 in Eq.(8.15), we get

$$V_O = A_{OL} (V_I - \frac{R_I V_O}{R_I + R_F})$$

Rearranging, we get

$$V_O = \frac{A_{OL} (R_I + R_F) V_I}{R_I + R_F + A_{OL} R_I}$$

$$A_{CL} = \frac{V_O}{V_I} = \frac{A_{OL} (R_I + R_F)}{R_I + R_F + R_I A_{OL}}$$

Since the value of A_{OL} is ideally infinite, and for op amp **741C** it is 200,000, i.e. $\sim 10^5$, therefore

$$A_{OL} R_I >> R_I + R_F$$

Thus

$$A_{CL} = \frac{A_{OL} (R_I + R_F)}{A_{OL} R_I} = \frac{R_I + R_F}{R_I}$$

$$A_{CL} = 1 + \frac{R_F}{R_I}$$

Thus the equation for A_{CL} for the non-inverting amplifier is same as obtained earlier in section 8.3 through the **Eq.(8.7)**. Hence the assumptions made by us in the beginning did not cause any mathematical error, rather helped us solving various networks in a simplified way.

8.8 SUMMARY

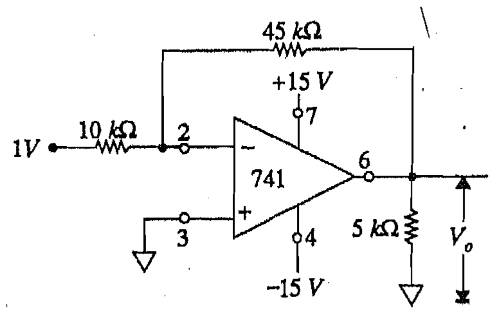
- **Infinite** open loop gain of an ideal op amp is of no use in most of the applications of the op amp, and therefore **external circuitary** is used to control the gain of the amplifier.
- With the use of the feedback resistor R_F connecting pins 6 and 2, the closed loop gain of an op amp can be controlled.
- Inverting amplifier gain is absolutely dependent on the feedback resistor R_F and input resistor R_I. Negative sign in the equation for its gain means that there is a phase change of 180° between the input voltage and the output voltage. Because of this reason, it is called inverting amplifier. Input voltage is supplied to pin 2 in this case.

- Inverting amplifier can be used as a multiplier and divider.
- In non-inverting amplifier, there is no phase change between the input and output voltages. The input is given to the pin 3. The closed loop gain of this amplifier is always greater than unity.
- Inverting amplifier can have several inputs with common feedback resistor Such a circuit can be used as an adder, average and channel amplifier.
- In a basic differentiator, the input resistor is replaced by a capacitor. The output waveform of the differentiator is the derivative of the input waveform.
- In a basic integrator, the feedback resistor is replaced by a capacitor. The output waveform of the integrator is the integral of the input waveform.
- Closed loop gain of the op amp can also be derived from the negative feedback considerations. Such a derivation shows that the assumption of pins 2 and 3 at the same potential, though not exactly true, helps us in deriving results in a simplified way.

8.9 TERMINAL QUESTIONS

1) Design an amplifier using op amp 741C for a gain of –20 for an input of 0.5 V and an output current of 5 mA.

2) Identify the circuit given below and determine the amount of output current. What changes should be made in the circuit so that output current is doubled without changing the gain of the amplifier?



3) Design an amplifier using op amp 741C for a gain +19. If the input voltage of 0.5 V is to be amplified with an output current of 5 mA, determine the value of the load resistor.

4) Design a two-channel amplifier with gains –8 and –17.

5). Design a differentiating circuit the output of which is twice the derivative of the input signal:

6) 'Design an integrating circuit the output of which is one-fifth the integral of the, input signal.

8.10 SOLUTIONS AND ANSWERS

SAQs

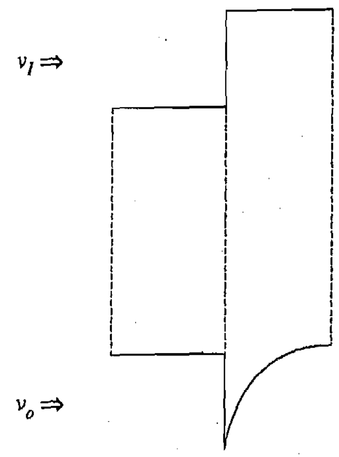
1. The output voltage is $-V_{SAT}$. (Note that the gain of the amplifier is –10. With +2V input, the output should be –20 V. However, the output cannot be greater than $+V_{SAT}$ and less than $-V_{SAT}$. Therefore the output is $-V_{SAT}$ which is approximately –13 V.)

2. This is a non-inverting amplifier and its gain is $1 + R_F/R_I$. With R_F = 75 kΩ and R_I = 15 kΩ, the gain of the amplifier is *6*.

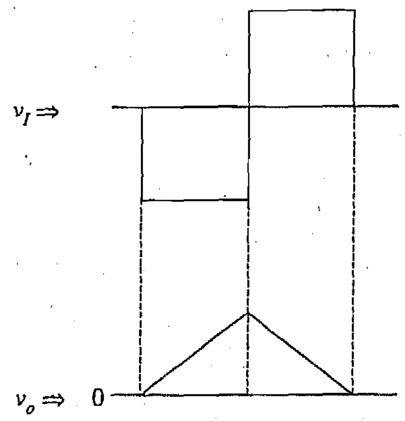
3. The circuit is far an inverting adder. The output voltage is

$$V_O = -\frac{70\ \text{k}\Omega}{10\ \text{k}\Omega}\ (5 - 3 + 1)\text{V} = -7 \times 3 = -21\text{V}$$

4. The output waveform is as given below.



5. The output waveform is as given below.



TQs

1) Choose the value of R_I = 10 kΩ. Therefore, for A_{CL} = 20,

   $R_F = -A_{CL}.R_I$ = 200 kΩ.

   Now I = 0.5 V/10 kΩ = 0.05 mA.

   $I_O = I + I_L$ = 5 mA = 0.05 mA + I_L

   Or I_L = (5 − 0.05) mA = 4.95 mA.

   Now $I = V_O/R_L$ = 10 V/R_L = 4.95 mA.

   Or R_O = 10 V/4.95 mA = 2.02 kΩ.

   Therefore, the required design is R_I = 10 kΩ, R_F = 200 kΩ, and R_L = 2 kΩ. **Use** ±15 V power supply.

2) The given circuit is for an inverting **amplifier with gain = −4.5**. The output voltage is −4.5 V.

   Now $I_O = I + I_L$ = 1 V/10 k + 4.5 V/5 kΩ

   = 0.1 mA + 0.9 mA = 1 mA.

For doubling the output current without changing the gain of the amplifier, I_L should be = 1.9 mA.

Therefore, R_L = 4.5 V/1.9 mA = 2368 Ω.

Thus, the value of R_L should be reduced from 5 kΩ to 2368 Ω.

3) The (+) sign with gain +19 means that a non-inverting amplifier is desired the gain of which is $1 + R_F/R_I$. It means that R_F/R_I should be 18. Choose R_I = 10 kΩ, then R_F = 180 kΩ. The output voltage is V_O = 19 x 0.5 V = 9.5 v.

Now $I_O = I + I_L$ = 5 mA = 0.5 V/10 kΩ + I_L

or I_L = (5 − 05) mA = 4.95 mA.

or $R_L = V_O/I_L$ = 9.5 V/4.95 mA = 1919 Ω.

Thus the required design is R_I = 10 kΩ, R_F = 180 kΩ, and R_L = 1919 Ω or ≈ 2 kΩ.

4) This is a two input inverting adder. Choose R_{I1} for channel-1 with gain −17. Therefore, R_F = 170 kΩ which is common to both the inputs. To find R_{I2} for the channel-2, we have R_F/R_{I2} = −8. Or R_{I2} = 170 kΩ/8 = 21.25 kΩ.

Thus the required design is R_{I1} = 10 kΩ, R_{I2} = 21.25 or ≈ 20 kΩ. R_F = 170 kΩ, and choose R_L = 5 kΩ (as no current requirement is stated).

5) Basic differentiator output is $V_O = -R_F C_I \mathrm{d}v_I/\mathrm{d}t$. Given is $R_F C_I$ = 2. Choose C_I = 1 μF, then R_F = 2 MΩ so that $R_F C_I$ = 2.

Thus with C_I = 1 μF and R_F = 2 MΩ, the output will be twice the derivative of the input signal.

6) Basic integrator output is $V_O = -\frac{1}{R_I C_F}\int V_I \mathrm{d}t$

For the output to be one-fifth of the integral of the input, $R_I C_F$ should be = 5. Therefor, choose C_F = 1 μF, then R, = 5 MR so that $R_I C_F$ = 5. Thus, with R_I = 5 MΩ and C_F = 1 μF, the output of the basic integrator will be one-fifth of the integral of the input signal.