UNIT 7 THE OPERATIONAL AMPLIFIER

Structure

7.1 INTRODUCTION

Operational Amplifier (Op Amp) was first designed in 1948 based upon a single vacuum tube. The primary use of early op amps was in analog computers. The op amps derived their first name 'operational' basically because at that time they were used in mathematical operations such as addition, subtraction, multiplication, division and solving differential equations.

The limited accuracy of analog computers upto three significant figures had limited their use. They were lather replaced by digital computers which were faster, more accurate and versatile.

With the advancement of integrated circuit (IC) technology, several types of IC based op amps were produced in mid-sixties which were available in the market. Those op amps required much lower power as compared to the discrete components based amplifiers, They were cheaper and needed much less space. With such op amps commercially available, the task of designing circuits became very easy With one or two op amps and a few resistors or some other components, very good quality amplifiers, signal generators, modulators, etc. could be made.

The sophistication in the recent times in the IC technology enabled the manufacturers to produce special purpose op amps. The dual and quad op amp packages have two and four op amps respectively on a single chip. They are commercially available and are quite cheap.

For the user of an op amp it is not at all necessary to know the actual circuit of the operational amplifier which is grown on a single chip. The user neither derives any information from the circuit nor can change it. What the user needs is the performance characteristics of the op amp available in the data sheet supplied by the manufacturer. With such characteristics known, the user can use the op amp in any application where they fit in.

Objectives

After studying this unit, you should be able to :

- draw a schematic symbol for an op amp,
- distinguish between two types of packages of op amp IC,
- draw the pin-out diagram for op amp 741C,
- identify the manufacturer's name and temperature range of an op amp by noting the number code printed on the IC,
- explain the power supply requirements for op amps,
- state precautions which have to be borne in mind while working with op amps,
- establish input-output relationship for op amps,
- define input offset voltage, output offset voltage, differential input resistance, output resistance, common mode rejection ratio, maximum output current, power consumption, slew rate and gain bandwidth product,
- distinguish between the characteristics of ideal op amp and of 741C.
- describe the equivalent circuit of an op amp,
- draw the ideal voltage transfer curves for an op amp,
- describe comparators and zero crossing detector.

7.2 TECHNICAL DETAILS OF OP AMPS

Before learning the usage of op amp, we shall learn some general technical details of op amps and associated requirements in this section.

7.2.1 Symbol

The symbol used for op amp is shown in Fig.7.1. It is a triangle pointing to the signal flow. This symbol also shows part identification numbers (PIN) for a general

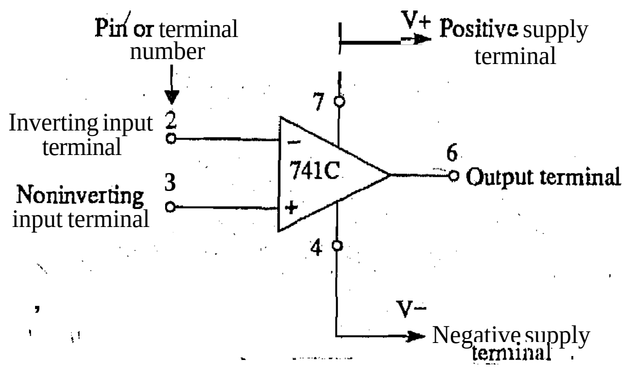


Fig.7.1: Circuit symbol for an op amp.

purpose and very popular op amp 741C. All op amps have at least five terminals—two for inputs, two for power supply and one for the output. General purpose 741C has other terminals as well.

The op amp input has two terminals. Pin **2** is named inverting input because when the input is given to it, the output at pin *6* is available with 180 degree phase change. Pin **3** is named non-inverting input because when the input is given to it, the output at pin *6* is available without phase change. Therefore, pin 2 is quite often shown with a (–) sign and non-inverting input with a (+) sign. These (–) and (+) terminals are quite often known as differential input terminals. The output voltage depends upon the difference in voltages between them.

Negative voltage terminal of the dual power supply is connected to pin 4 and positive voltage terminal is connected to pin 7. Note that if the polarities of the voltages applied to pins 4 and 7 are reversed the op amp shall be damaged and cannot be used.

SAQ 1

What are the numbers of input and output pins?

7.2.2 Package

The op amp which is fabricated on a silicon chip is housed in a suitable package. Op amp 741C is available in two most popular packages (a) metal can and (b) dual-in-line packages (DIP). These packages are shown in Fig.7.2 (a) and (b) respectively. The combination of the op amp symbol and package view is quite commonly used by the manufacturers in their data sheets. These combinations are shown in Fig.7.3 (a) and (b) respectively.

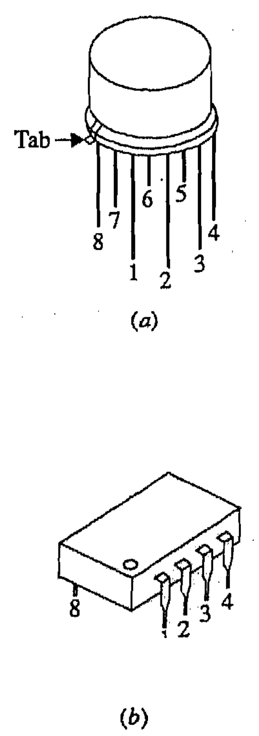
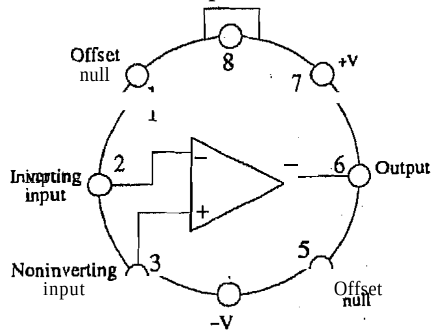
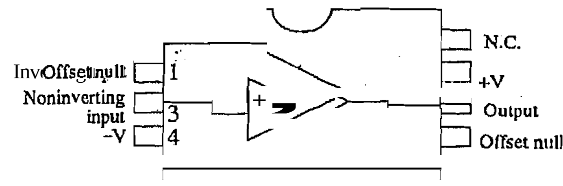


Fig.7.2: Op amp packages. (a) Metal can, and (b) 8-pin DIP package.



(a) 8-lead metal can
(TO-99), top *view*



(b) *8-lead* mini. *dip*
top view

Fig.7.3: Pin diagrams for (a) metal can, and (b) 8-pin dip package of op amp. NC means no connection.

The pin count of every IC including op amps is done as follows. Look at the top view of the IC and note the position of a notch or a dot in case of DIPs and a tab in case of a metal can package. The notch or dot or tab identifies the pin 1 which is on its left. Then other pins are counted counterclockwise. Here is caution. Never count looking at the bottom view.

SAQ 2

What is the way in which the IC pins are counted?

7.2.3 Number Code

On the package of the IC including op amps some numbers are printed with the help of which the IC is identified. On op amp package, say in a typical IC, CA741CP is printed. The first two letters 'CA' identify the manufacture's code. CA is the code for RCA, AD is for Analog Devices, LM is for National Semiconductor Corp, μA is for Fairchild, etc. The word 741C is the circuit designator for commercial purpose op amp. This word for any other IC could be of three to seven numbers and letters. In 741C, C identifies the commercial temperature range (0 to 70°C). Other temperature codes are I for industrial purpose (–25 to 85°C) and M for military purposes (–55 to 125°C). Last letter P stands for plastic package.

SAQ 3

Identify the IC with number code LM741I.

7.2.4 Power Supply

For supplying bias to a general purpose op amp (741C), a bipolar power supply is required. Commercially available dual power supplies which give voltages (+15)–0–(–15)V or (+9) –0– (–9)V are used with the op amps. Such voltage ranges are quite often mentioned as ±15 V or ±9 V. Two equal voltage sources as shown in the Fig.7.4 can also be used with a common terminal.

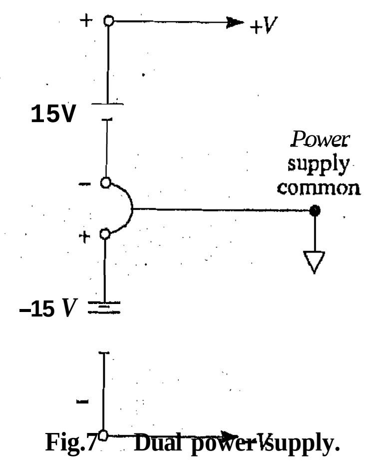


Fig.7.4 Dual power supply.

SAQ 4

Name-the pins of op amp 741C to which power supply is connected.

7.2.5 Precautions

A circuit in which op amp is being used is made either on a breadboard or on a printed circuit board. There are certain precautions in making and using the circuit which must always be borne in mind.

- Do the entire wiring of the circuit with power supply off.
- Use Wires as short as possible.
- All ground connections should meet at a common point.
- First of all, power (±V) should be supplied to the op amp.
- Apply signal only after op amp is supplied power.
- Always measure voltages and not currents. The current may be found by finding voltage at two ends of a resistor.
- When the work is over, remove signal first and then switch off op amp power supply.

It is necessary here to stress further that never, never

- reverse the bias polarity,
- apply signal voltages greater then +V and less than –V,
- connect ac signal with op amp power off.

SAQ 5

Can you connect positive terminal of the dual power supply to pin 4 of op Amp 741C and negative terminal to pin 7? Why?

7.3 CHARACTERISTICS OF OP AMPS

The ideal characteristics of an operational amplifier will be outlined in detail later. For the time being, it should be remembered that an ideal operational amplifier has infinite voltage gain, infinite input impedance and zero output impedance.

Actual characteristics of an op amp are as a matter of fact different.

7.3.1 Input-Output Relationship

As pointed out earlier, op amp amplifies the difference of voltage present between the input pins 3 and 2. If the difference voltage is V_D and the gain of the op amp is A, then the output voltage is AV_D. In Fig.7.5, the voltage at pin 3 is designated to be V_1 and at pin 2 it is V_2 Thus

$$V_D = V_1 - V_2$$

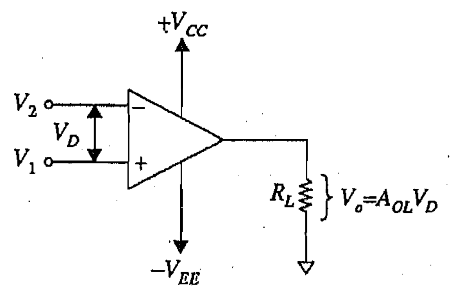


Fig.7.5: Output voltage depends on the input difference voltage.

and the output voltage is

$$V_O = A(V_1 - V_2) = AV_D$$

This gives the voltage gain

$$A = \frac{V_O}{V_D}$$

The voltage gain A in this equation is referred to by several names—large signal voltage gain *(LSVG)*, open loop **gain** (A_{OL}) or **Differential** voltage gain (A_D).

Remember that the difference voltage, V_D, has been calculated as follows:

$$V_D = \text{voltage at pin 3 } (V_1) - \text{Voltage at pin 2 } (V_2)$$

Both V_1 and V_2 *are* measured with respect to the ground. Note that the gain of the ideal operational amplifier is infinite, while for the realistic, say **μA741C,** the gain is **200,000.** Thus theoretically, the output voltage should be 200,000 times V_D. But one cannot obtain from any amplifier a voltage which is greater than the bias voltage supplied by the power supply. **Therefore,** the output voltage gets stuck to the bias voltage. Actually, the op amps consist of several transistors across **which** certain voltages are dropped so as to maintain their proper functioning. This limits the output voltage below the bias voltage. **The** upper limit of the output voltage V_O is the positive saturation voltage, $+V_{SAT}$ and the lower limit is the negative saturation voltage, $-V_{SAT}$. In the case of the general purpose op **amp biased** with ±15 power supply the $+V_{SAT}$ and $-V_{SAT}$ *are* $+14\,V$ and $-13\,V$ **respectively restricting** .the peak-to-peak **symmetrical** swing to 13 V. It should now be **remembered** that if the input to pin 3 is greater than that to pin 2, then V_D is **positive** and the output is above ground and is $+V_{SAT}$. And if the input to pin 2 is greater than that to pin 3, **then** V_D is negative and the output is below ground and is $-V_{SAT}$.

SAQ 6

How do you calculate input difference voltage to an op amp?

7.3.2 Input Offset Voltage

Input **offset** voltage. is the voltage which **is** applied between pins 2 and 3 so as to get zero output at pin 6. If the dc input voltages **applied** to pins 3 and 2 are V_1 and V_2 *as* shown in **Fig.7.6,** then the input offset voltage is $V_{10} = V_1 - V_2$ with zero output voltage. The value of V_{10} can be positive or negative. The smaller is the **value** of V_{10}, better'is the matching of input terminals. For 7416, the maximum value of V_{10} is 6 mV.

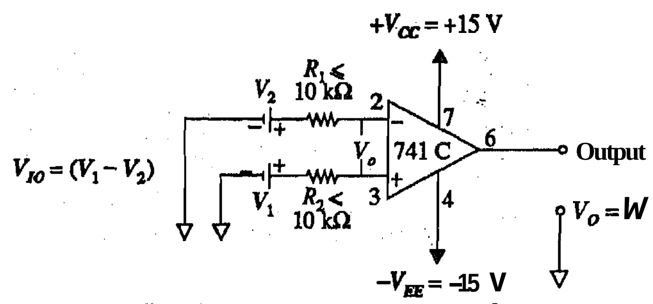


Fig.7.6: Measuring Input offset voltage.

7.3.3 Output Offset Voltage

Output voltage of an op amp should be **ideally** zero when both the inputs are zero or grounded. However, it may not be so. Some output voltage may be available with both the **inputs** grounded. This voltage is known as output offset voltage and it should be made zero, otherwise the results will be inaccurate.

To reduce the output offset voltage to zero, a carbon potentiometer of high resistance, **say** 22 kΩ, is connected between the pins 1 and 5, and the wiper is connected to pin 4 as shown **in Fig.7.7.** Adjust the position of the wiper so that output offset voltage **is reduced to zero.** In **case** the output offset voltage is not reduced to zero despite the

adjustments, then a voltage compensating network is designed (which is beyond the course of this **unit**).

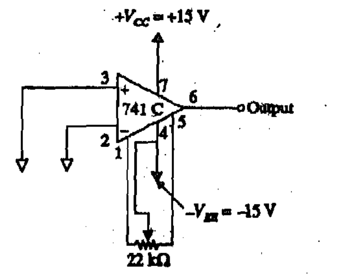


Fig.7.7: Adjusting output offset voltage.

SAQ 7

What is the output offset voltage?

7.3.4 Differential Input Resistance

Differential input resistance, R_I is generally referred to as the input resistance of the op amp. This is the equivalent resistance which can be measured at either of the inputs-inverting or non-inverting with the other **terminal** grounded, Ideally this resistance is infinite. But in case of **741C,** R_I is 2 **MΩ**.

7.3.5 Output Resistance

Output resistance, R_O is the equivalent resistance measured between the output pin 6 and the ground. Ideally the value of R_O is zero, but for 741C it **is 75Ω.**

7.3.6 Common Mode Rejection Ratio

There may be situations when the op amp is being used in a noise environment. The pins 2 and 3 may pick up same noise voltages. **Since the** op amp amplifies the difference in voltage at the two inputs, therefore with the same voltage present **at** the two inputs the output voltage due to noise should be ideally zero thus **cancelling** unwanted noise **singles**. To assess whether both the inputs are properly matched **for** this purpose a **term** known as common mode rejection ratio **(CMRR)** is **wed.** It **is defined** by several manufacturers in several ways which are essentially equivalent. It is defined **as** the ratio of the open loop voltage gain, A_{OL}, to the **common mode** voltage gain, A_{CM}.

$$\text{CMRR} = \frac{A_{OL}}{A_{CM}}$$

The common mode voltage gain, A_{CM}, is obtained **as** shown in **Fig.7.8. Both** the inputs are connected to each other and given the **same** common mode voltage, V_{CM} and the common mode output voltage V_{OCM} is noted. Then the **common** mode **voltage** gain is

$$A_{CM} = \frac{V_{OCM}}{V_{CM}}$$

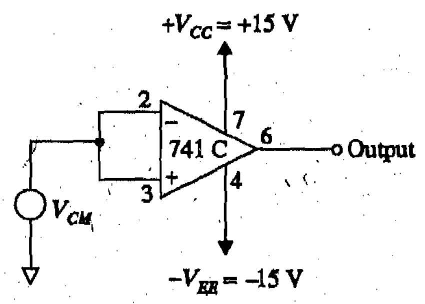


Fig.7.8: Common mode **connections.**

7.6 COMPARATORS

7.6.1 Voltage Level Detector

Recall that an operational amplifier is a difference amplifier and that its maximum output voltage is $\pm V_{SAT}$. Fig.7.11 shows a circuit for an op amp used as a comparator. **A** fixed reference voltage V_{REF}, say of 1V, is applied to inverting input pin 2. The time dependent signal V_{in} is applied to the non-inverting input pin **3**. The output voltage V_O is

$$V_O = AV_D$$
$$= A(V_{in} - 1V).$$

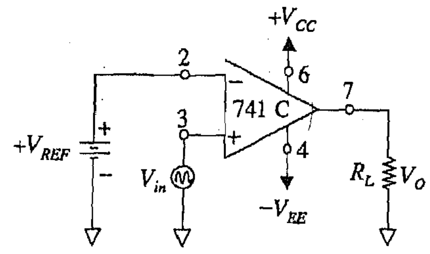
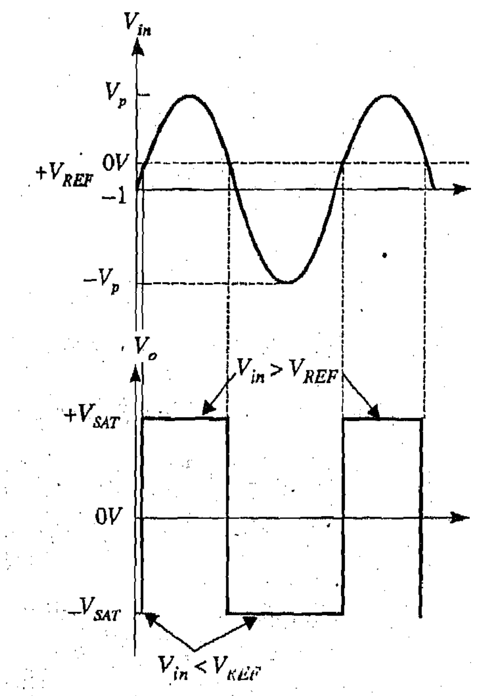


Fig.7.11: Comparator or voltage level detector.

Now, if $V_{in} = 1V_D$, then $V_D = 0$. Hence $V_O = 0$ as shown in Fig.7.12 and 7.13. If $V_{in} > 1$V, then V_D is positive. In this case the output gets limited to $+V_{SAT}$ as shown in Fig 7.12. If $V_{in} < 1$V, then V_D is negative which limits the output to $-V_{SAT}$. Thus at any instant of time the output voltage V_O shows whether the input is greater than V_{in} or less than V_{in}. This circuit acts like an analog to digital converter. This non-inverting comparator is also known as voltage level detector. The value of V_{REF} can be 0, or any value positive or negative. It can also be connected to **any** of the inputs. However, to find the output waveform, one must note whether V_D is positive or negative. If the reference voltage V_{REF} is connected to the non-inverting input pin **3** and the input signal is given to pin **2**, the coinparator is known as inverting comparator.



Fie.7.12: Output waveform of the comparator with $+V_{REF}$

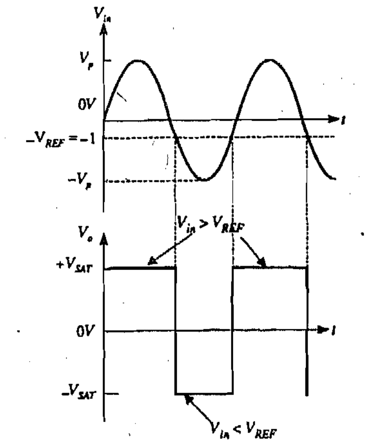


Fig.7.13: Output waveform of the comparator with $-V_{REF}$.

7.6.2 Zero Crossing Detector

The zero crossing detector is an application of comparators. Fig.7.14 shows a circuit for zero crossing detector in which pin 3 is grounded making the ground potential (OV) to be the reference voltage. The input signal is given to pin 2. When the V_{in} exceeds OV, then V_D is negative and the V_O is limited to $-V_{SAT}$. Likewise, when V_{in} is less than 0V, then V_D is positive and the V_O is limited to $+V_{SAT}$. Thus the output voltage shows whether the input voltage is above or below the zero level as is shown in Fig.7.15.

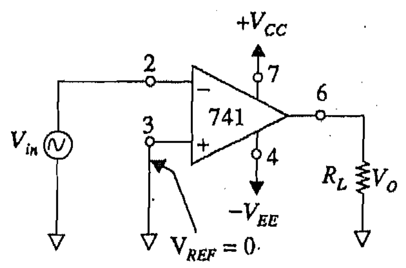


Fig.7.14: Zero crossing detector.

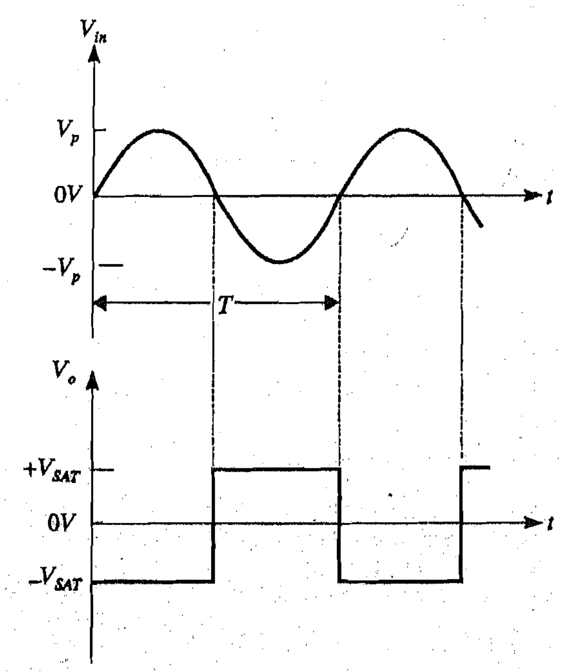


Fig.7.15: Input and output waveforms of a zero crossing detector.

SAQ 9

Trace the output voltage waveform of the circuit given in **Fig.7.16.**

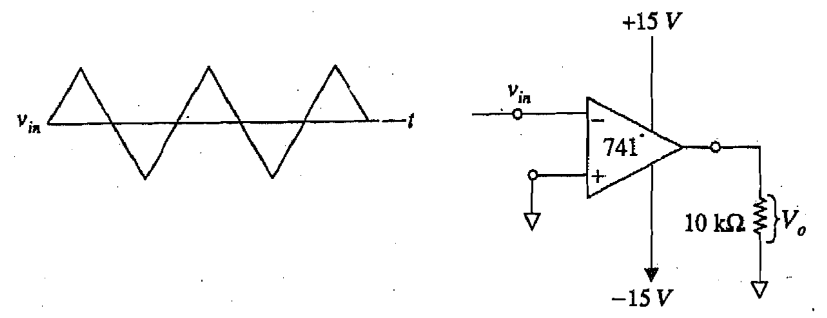


Fig.7.16

7.7 SUMMARY

- Several manufacturers use a combination of op amp symbol and IC package to give the pin-out diagram.
- The name of the manufacturer the op and amp temperature range can.be found out by reading the number code printed on the top of the IC package.
- A dual power supply is needed to operate the op amp.
- Input signal should be given to the op amp only after supplying bias voltage to it.
- Polarity of the bias supply voltages to pin 4 and 7 should never be reversed.

  The ideal operational amplifier has infinite voltage gain, input resistance, CMRR and slew rate.
- The ideal operational amplifier also has zero output resistance and output offset voltage.
- The realistic characteristics are markedly different than the ideal characteristics. However, in comparative terms they can be taken to be ideal.
- The equivalent circuit of an ideal op amp is quite often used in the analysis of the basic operating principles of op amps.
- The voltage transfer curve of an op amp is the curve between the output voltage and the difference input voltage.
- Comparators are basically voltage level detectors with reference voltage source connected to either of the inputs of the op amp. Reference voltage can be 0, positive or negative.
- Inverting and non-inverting comparators and zero crossing detectors are used in many applications,

7.8 TERMINAL QUESTIONS

1) Give the pin-out diagram of op amp DIP 741C.
2) What are the precautions that must always be kept in mind while working with op amps?
3) Distinguish between characteristics of an ideal op amp and that of 741C.
4) Trace the output waveform of the circuit given in Fig.7.17.

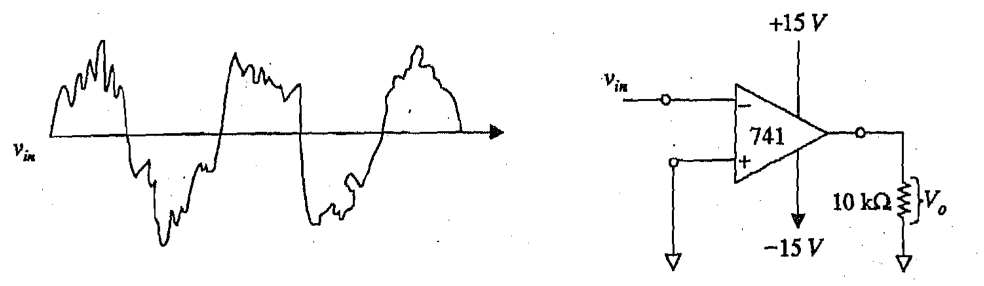


Fig.7.17

5) If the input pin 2 is grounded and a triangular wave input is given to pin 3, then what will be the output waveform?

7.10 SOLUTIONS AND ANSWERS

SAQs

1. **Inverting** input pin 2, **non-inverting** input **pin** 3 and the output pin 6,
2. See the tog view of the IC. Look for the notch or dot on the body of the IC. The pin on the left of the notch or dot is **pin 1**. Then start **counting** pins counter-clockwise.
3. For the IC with number **LM741I,** the letters LM identify the **name** of the manufacturer, National Semiconductor **Corp**. The letters 741 **indicate op** amp. The letter I indicates the **temperature** range for the industrial **purposes, i.e. –25°** to **85°C**. Thus **LM741I** means that it is **an op amp manufactured** by National Semiconductor **Corp,** for industrial purpose for a temperature range of **–25°** to **85°C**.
4. **Pins** 4 and 7. $-V_{EE}$ is connected to pin 4 and $+V_{CC}$ is connected to pin 7.
5. No. It will permanently damage the op amp.
6. Input difference voltage to an op amp V_D is calculated as follows:

   V_D = voltage at pin 3 (V_1) − voltage at pin 2 (V_2)
7. It **is the** voltage available at the output pin 6 even when both the input pins 2 and 3 **are** grounded.
8. No. Higher **is** the **CMRR**, better is the matching of input **terminals.**
9. The output **waveform** is as shown in Fig.7.18.

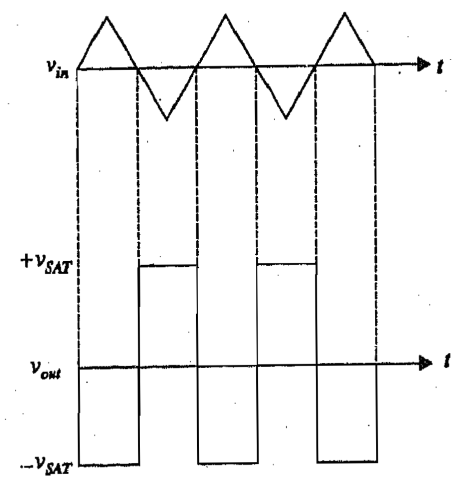


Fig.7.18

TQs

1) Given in Fig.7.3 (b).
2) Listed in section 7.2.5.
3) Given in section 7.3.11.
4) Output waveform is given in Fig.7.19.

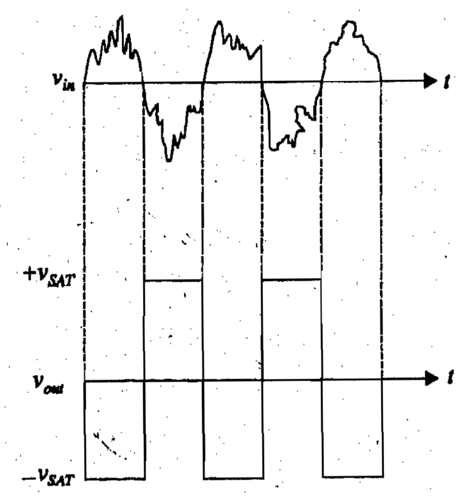


Fig.7.19

5) The circuit for this question and the output waveform are as shown in Fig.7.20.

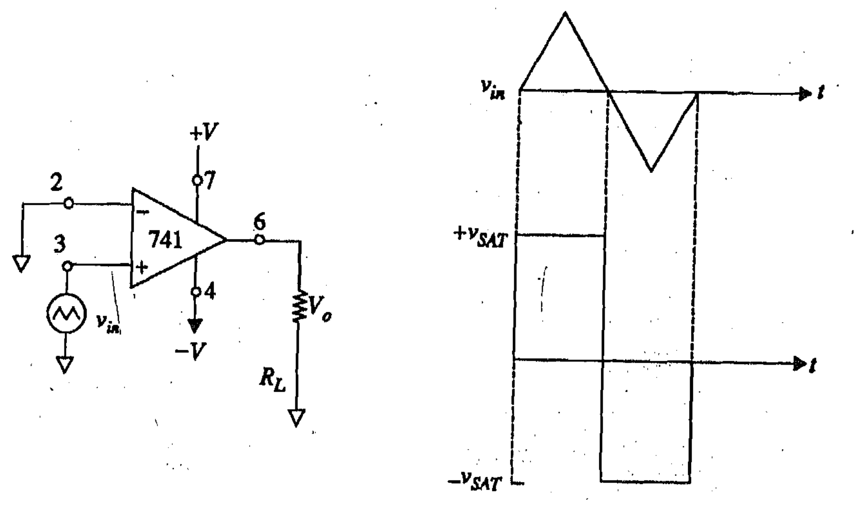


Fig.7.20