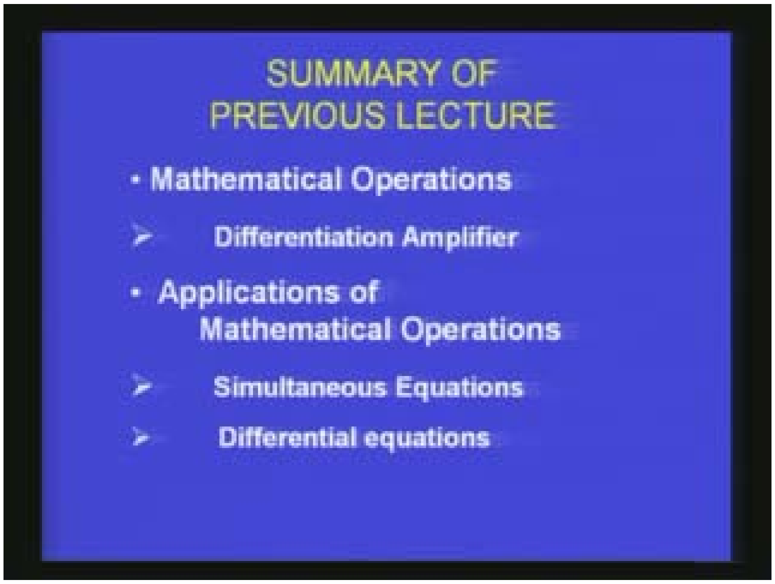
Basic electronics
Prof. T.S. Natarajan
Department of Physics
Indian Institute of Technology, Madras
Lecture- 27

Mathematical operations
(Difference Amplifier, Integeration Amplifier...)

Hello everybody! In our series of lecture on basic electronics learning by doing let us move on to the next one. Before do that we would recapitulate what we learnt in the previous lecture. You might recall we discussed about the various mathematical operations that can be performed with operational amplifiers.

(Refer Slide Time: 1: 46)



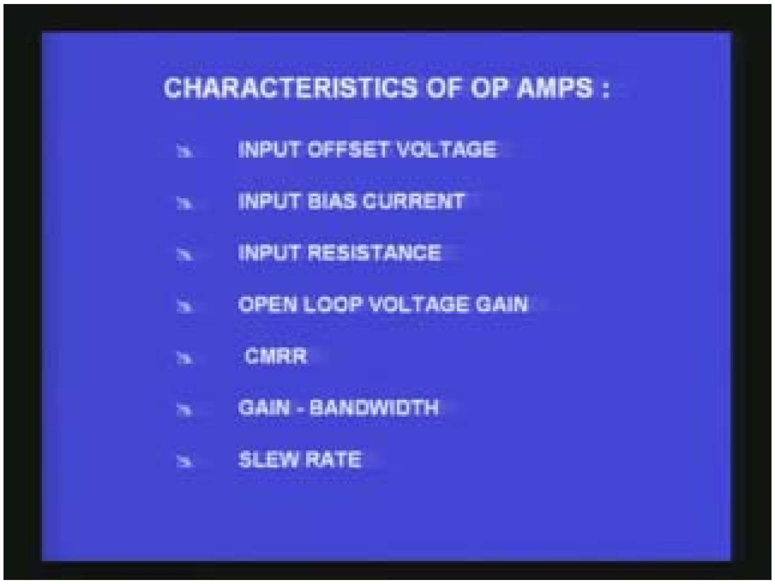
SUMMARY OF PREVIOUS LECTURE

- Mathematical Operations
  - ➢ Differentiation Amplifier
- Applications of Mathematical Operations
  - ➢ Simultaneous Equations
  - ➢ Differential equations

In the last lecture we saw how the mathematical operation of differentiation can be performed using the operational amplifier and we also saw some applications of different mathematical operations like summing, integration, differentiation, etc. The two examples that we discussed are basically solving simultaneous equations using operational amplifiers and also I gave an example of a simple second order differential equation including the damping factor. We discussed how that equation can be solved by using a set of integrators and providing feedback. In this lecture we would like to go into the actual characteristics of the operational amplifier.

From the time we discussed about operational amplifiers we talked about the importance of negative feedback and different application circuits based on negative feedback. Afterwards we saw why the name operational amplifier has come to stay and in that we discussed about the different mathematical operations that can be performed and some of the applications. We have to now look at the operational amplifier as a device and see its basic characteristics which help us to perform different circuit functions using operational amplifier. I have listed out in the screen the different characteristics of the op amp. I have not exhaustively included all the characteristics but I have put the most important characteristics of an operational amplifier.

(Refer Slide Time: 3:52)



CHARACTERISTICS OF OP AMPS :

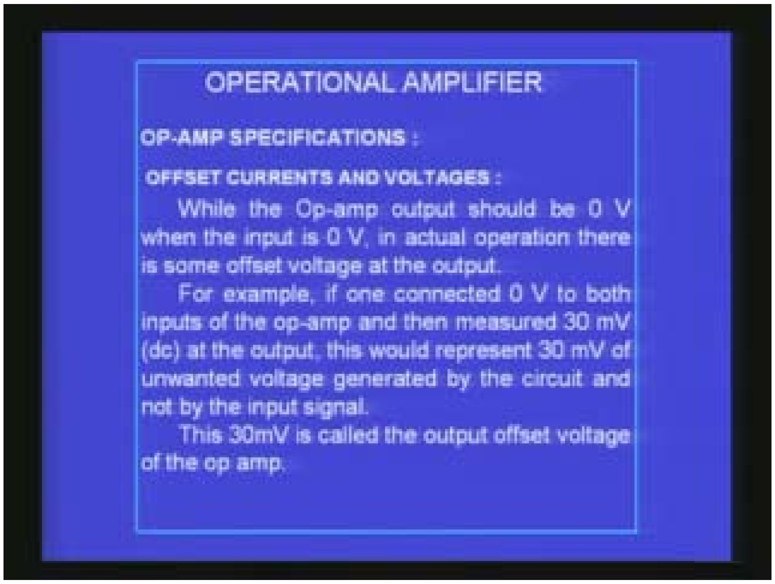
- INPUT OFFSET VOLTAGE
- INPUT BIAS CURRENT
- INPUT RESISTANCE
- OPEN LOOP VOLTAGE GAIN
- CMRR
- GAIN - BANDWIDTH
- SLEW RATE

The first characteristic is called input offset voltage. Then you have the input bias current, the input resistance which is a very important characteristic for any amplifier. The open loop voltage gain is actually the large gain that is obtained without providing any feedback. Then there is a quantity called as CMRR which is common mode rejection ratio which is also very important characteristic of differential amplifier. An operational amplifier being a differential amplifier it has got this important characteristic. Then we also would see the gain bandwidth product and how it is a constant and the last one which is the slew rate. What we would do is to take each one of these characteristics and define what we mean by the various characteristics and how do we measure for a given operational amplifier each of these characteristics.

Looking at the data manual is a very, very important step in doing electronics. For an operational amplifier if you look at the manufacturer data manual, the manufacture is most anxious to make you understand about the complete characteristics of the op amp so that you will be able to exploit these characteristics in different application circuits and the manufacturer data manual is a very, very important document for anybody who wants to practice practical electronics. Each one of these different characteristics that I have listed would give the corresponding numbers for the operational amplifier that you are looking at. If it is for example 741, which is the most popular operational amplifier that we have been using also the various parameters like input offset voltage, the CMRR, the open loop voltage gain, etc for all will be listed in the data manual so that when we measure we can also see whether they correspond to what the manufacture himself claims as the corresponding quantity. We also should perhaps bear in mind that these characteristics are very specific to the dc conditions that you provide. For example the power supply voltage that you used and the operating frequency. Usually the manufacture will also mention the operating conditions; the temperature, the various power supply voltages, the signal frequency, etc before they specify the various characteristics. We should also bear in mind that the characteristics can vary slightly when we change these conditions like the power supply voltage.

With this back ground let us move on to the first of the different characteristics which is input offset voltage. There are two things that you normally worry about when it comes to the input side of an operational amplifier with reference to offset and that is the offset current and the offset voltage.

(Refer Slide Time: 7:11)



OPERATIONAL AMPLIFIER

OP-AMP SPECIFICATIONS :

OFFSET CURRENTS AND VOLTAGES :

While the Op-amp output should be 0 V when the input is 0 V, in actual operation there is some offset voltage at the output.

For example, if one connected 0 V to both inputs of the op-amp and then measured 30 mV (dc) at the output, this would represent 30 mV of unwanted voltage generated by the circuit and not by the input signal.

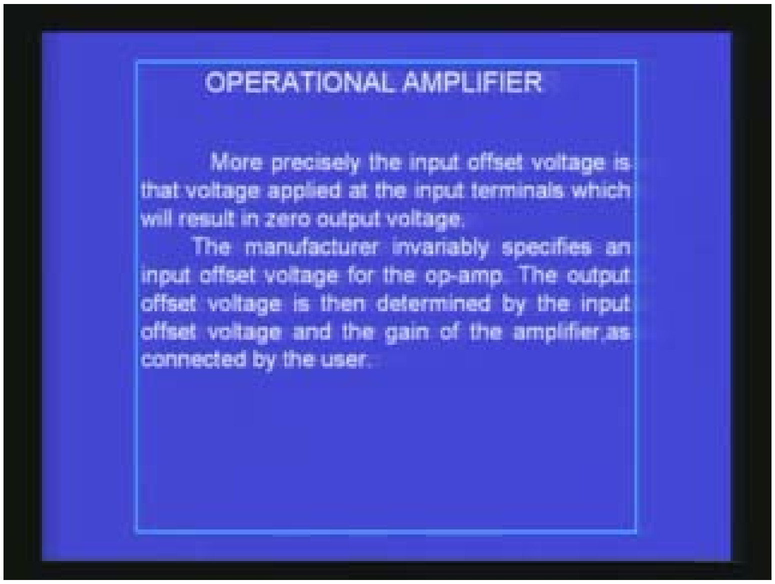
This 30mV is called the output offset voltage of the op amp.

You also have two different types of offset voltages; the input offset voltage and the output offset voltage. We should try to understand the meaning of all these terms before we go into the actual measurement. What we normally expect in an amplifier? If it is a linear amplifier the output is proportional to the input. That is what we mean by linear operational amplifier. If I connect zero voltage at the input the signal is zero. If I apply zero voltage, the output should be zero also. But in a practical operational amplifier or in any amplifier for that matter even when you give zero input which corresponds to connecting the input terminal to the ground potential invariably there will be a very small but finite voltage at the output. That means what? Without giving any input you seem to be getting an output even though small. This output that you get when you make the input voltage zero is what is called output offset voltage of the amplifier. This as I already mentioned to you will depend upon the applied power supply voltage and various other environmental conditions.

For example I have indicated here if one connected zero volts to both the inputs of an op amp and measured 30 millivolts dc at the output then this 30 millivolts of unwanted voltage generated by the operational amplifier circuit itself without any input is what is called the output offset voltage of the amplifier. You can also look at in another way. Why are you getting an output offset voltage? Why are you getting an output voltage? There should be an input voltage if the amplifier is a good one. This output voltage for example that 30 millivolts that I was talking about has come about because of some spurious input voltage that has come which when amplified by the gain of the amplifier corresponding to the configuration that you use is the reason why you are getting the output offset voltage. You can take that stand. If you do that then you must give another voltage at the input which is opposite to this voltage source which will only make the output zero. That means if I want to make the output voltage zero I must give an input voltage in a proper polarity so that it takes care of the spurious input sources that might be there which is responsible for the output voltages. How we normally define the input offset voltage is by saying that it is the input voltage that I should apply at any one of the two inputs in the case of the operational amplifier to make the output zero. This is what we call input offset voltage. This input voltage because it is an opposite polarity will nullify whatever spurious input voltage that you have without connecting anything so that the total input voltage becomes zero and when you multiply that by the gain of the amplifier the output voltage is also zero because anything multiplied by zero is zero.

The manufacturers as I already mentioned to you invariably specifies an input offset voltage for the amplifier and normally the output offset voltage can be calculated by looking at the gain of the amplifier.

(Refer Slide Time: 11:15)



OPERATIONAL AMPLIFIER

More precisely the input offset voltage is that voltage applied at the input terminals which will result in zero output voltage.

The manufacturer invariably specifies an input offset voltage for the op-amp. The output offset voltage is then determined by the input offset voltage and the gain of the amplifier as connected by the user.

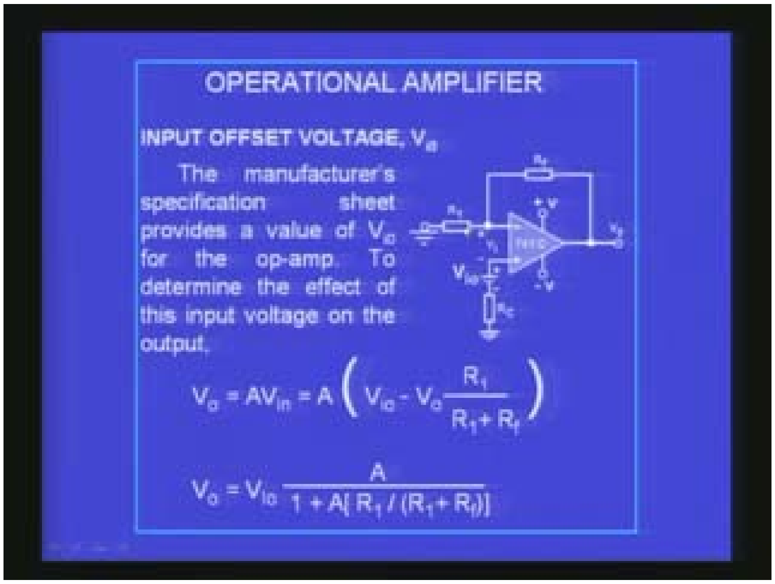
The gain of the amplifier will depend upon the configuration that we use. If it is an inverting amplifier the gain is R_2 by R_1 or - R_F by R_i. We have already seen those in the earlier lectures and if it is a non-inverting amplifier the gain is 1 plus R_2 by R_1 where R_2 is the feedback resistor and we know for a given configuration what is the gain and if you know what is the input offset voltage you multiply the input offset voltage by the gain that will be the output offset voltage of the amplifier.

Let us now look at the output offset voltage in much more general terms. I have already explained to you that the output offset voltage can be due to some spurious input voltage which has come due to some imbalances inside the amplifier configuration. There is also another source for the output offset voltage. Apart from the input offset voltage. It can come about due to another reason also and that reason is you have two input terminals for a given operational amplifier. If you look at the inverting and the non-inverting amplifier if I actually go into the amplifier through those terminals you are actually entering into the base of two transistors connected in a differential amplifier configuration. The two inverting and non-inverting amplifier terminals are basically the terminals of two bases of the two transistors which are connected at the input stage as a differential amplifier. If an amplifier should work there should be a finite current flowing into the base of the transistor. Then only the transistor can act as an amplifier. You require a minimum current. This minimum current we call the bias current.

We have already talked about the biasing of transistors in some earlier lectures and there should be some finite but minimum current flowing through the input terminals of an op amp to make the op amp work as an amplifier. These input currents are called input bias currents. They will be very, very small compared to the normal currents that you will be discussing in a given circuit and you do have two currents at the two input terminals of an operational amplifier. In principle because it is a difference amplifier it is always sensitive to the difference in the two currents. So you would always expect if the offset voltage of an amplifier should be zero then these two input bias currents which flow into the two terminals should be equal. But the two input bias currents are equal only in an ideal case. In a normal amplifier there will be always some finite but small difference in the two input bias currents. This difference in the bias current also can cause the differential voltage at the input which again can be amplified by the gain of the amplifier and the output offset voltage can also arise from this difference in the two input bias currents. This difference in the input bias currents is called input bias current offset. In principle if you don’t apply any signal at the inputs of an operational amplifier we observe that we can also still measure a finite but small voltage at the output of the amplifier. This output offset voltage as we call it has got two contributions one from the spurious source that we already discussed about at the input side which is called the input offset voltage. The second one is due to the difference in the bias currents at the two input terminals of an operational amplifier which is responsible for providing additional differential voltage at the input which again gets amplified and comes out as an output offset voltage.

Before we go further let us understand about the input offset voltage. The manufacturer specifies usually the input offset voltage for a given amplifier under certain operating conditions. If I call that V_{IO} and for example I choose a configuration that we are all familiar with namely the non-inverting amplifier. You can see on the screen on the right side I have shown a non-inverting amplifier with R_f and R_i and the input terminal is connected to ground for the corresponding inverting terminal.

(Refer Slide Time: 16:59)



OPERATIONAL AMPLIFIER

INPUT OFFSET VOLTAGE, V_{io}

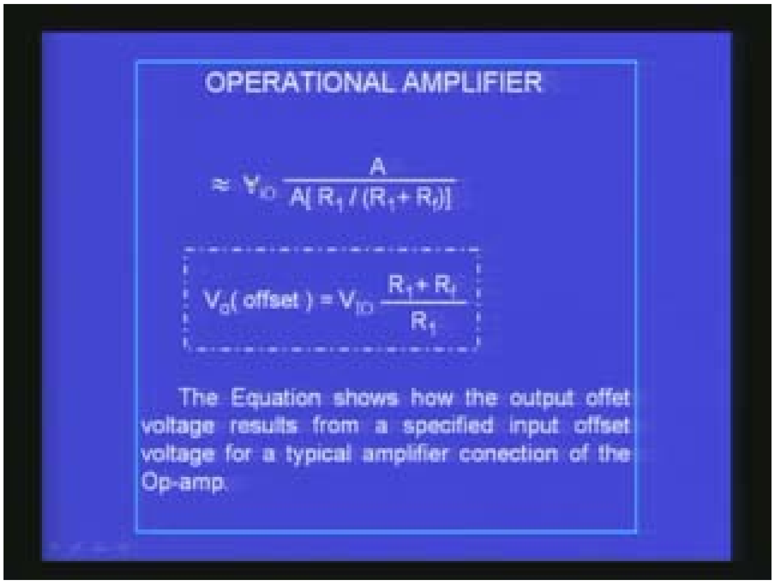
The manufacturer's specification sheet provides a value of V_{io} for the op-amp. To determine the effect of this input voltage on the output,

$$V_o = AV_{in} = A\left(V_{io} - V_o\frac{R_1}{R_1 + R_f}\right)$$

$$V_o = V_{io}\frac{A}{1 + A[R_1/(R_1 + R_f)]}$$

That V_{IO} I assume is something like a battery which has been connected at the input corresponding to the plus terminal. If you know this circuit you can calculate the output voltage. What is the output voltage? A is the gain. A times V_{in} the voltage impressed at the input and what is that V_{in}? The V_{in} now is actually V_{IO} that is there plus some voltage which got amplified due to the amplification which is corresponding to R_1 divided by R_1 plus R_f times V output. That is we are trying to calculate what will be the input voltage if I have V_o at the output. V_o is multiplied by 1 by gain. This R_1 plus R_f by R_1 is the gain and so it is put in the inversion here. R_1 divided by R_1 plus R_f and this gives you the input voltage that you would get corresponding to the output that you measure. The combination of this is what you will measure as the output. If I simplify this you can see V_o is equal to V_{IO} this V_{IO} multiplied by A divided by 1 plus A within bracket R_1 by R_1 plus R_f. What I have done is I have rearranged all the terminals corresponding to V_o and then rewritten this mathematical expression simplified. The output voltage is V_{IO} divided by this quantity. Because 1 is very small compared to the second term in the denominator, this second term will dominate most of the time and V_{IO} into A by A into R_1 divided by R_1 plus R_f is the expression effectively for the output voltage.

(Refer Slide Time: 19:01)



OPERATIONAL AMPLIFIER

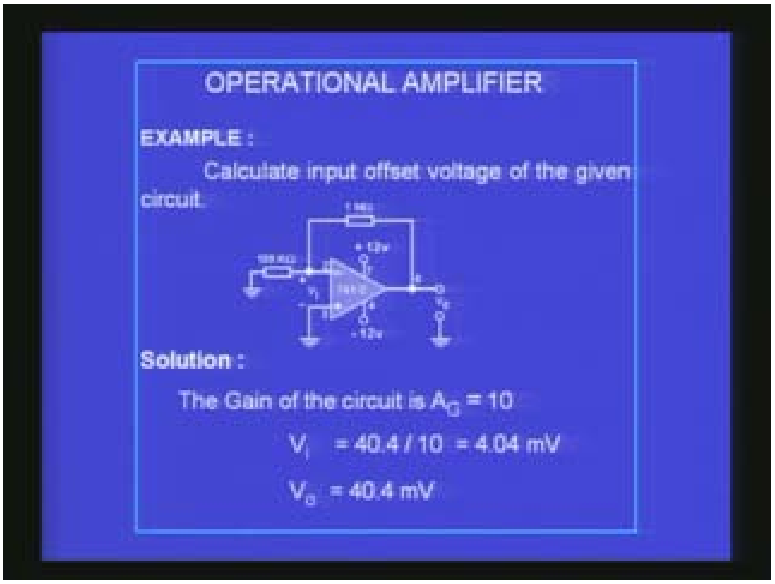
$$\approx V_{IO} \frac{A}{A[R_1/(R_1+R_f)]}$$

$$\boxed{V_o(\text{offset}) = V_{IO} \frac{R_1+R_f}{R_1}}$$

The Equation shows how the output offet voltage results from a specified input offset voltage for a typical amplifier conection of the Op-amp.

This output voltage is what we call the output offset voltage. In the next equation I have written V_o(offset) is nothing but V_{IO} into R_1 plus R_f by R_1 because these two A will cancel and the denominator of the denominator will go the numerator. V_{IO} into R_1 plus R_f by R_1 is the output offset voltage. This equation gives you a method of measuring or calculating the output offset voltage for a given configuration. In this configuration it is a non-inverting configuration. 1 plus R_f by R_1 is the gain of the amplifier and that is what I have written here. R_1 plus R_f by R_1 is nothing but 1 plus R_f by R_1. You multiply the input offset voltage by the gain. That is what you get as the output offset voltage.

(Refer Slide Time: 19:59)



OPERATIONAL AMPLIFIER

EXAMPLE :

Calculate input offset voltage of the given circuit.

Solution :

The Gain of the circuit is $A_G = 10$

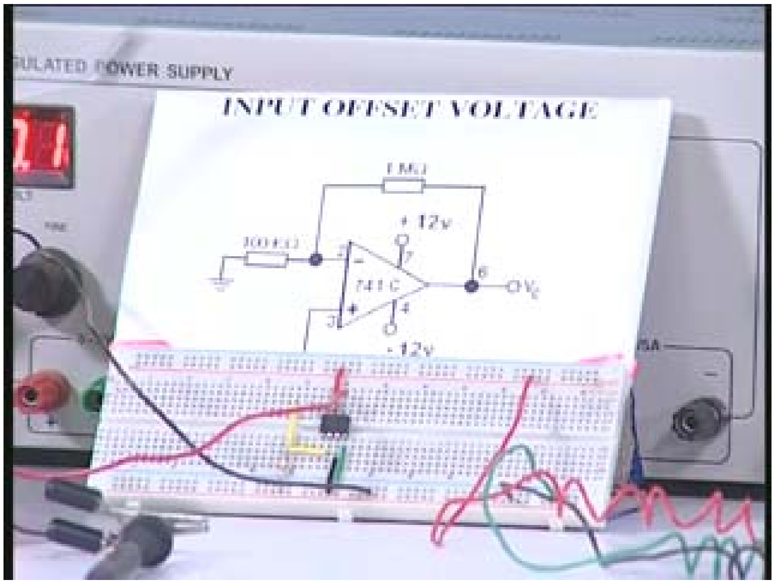
$V_i = 40.4 / 10 = 4.04$ mV

$V_o = 40.4$ mV

Let us now try to take a simple illustrative example as a small problem and try to understand how we can calculate the output offset voltage or the input offset voltage as the case may be. I have given some specific numbers here. R_f is 1 megohm in the circuit. 100 kilo ohm is the R_1 value and I now measure the output voltage. Because R_f is 1 megohm this is 10. The gain is about 10. The gain of the amplifier is 10. If the output voltage that I measure is 40.4 millivolts, I measure the output voltage using a multimeter for this configuration then I can calculate what should be the input offset voltage. Because I know the gain and I know the output voltage, output voltage divided by gain gives me the input voltage because output voltage is nothing but input voltage multiplied by the gain. V_i in this case which is actually V_{IO} the input offset voltage is 40.4 divided by 10 because the 10 is the gain and that is 4.04 millivolt which is reasonably a small value for most of the practical applications and the input offset voltage for a given configuration can be measured by constructing the amplifier and measuring the output voltage and divide the output voltage by the corresponding gain of the configuration that should give me the input offset voltage.

I will perform the experiment and perform the measurement on a given circuit which I showed you just now and let us see what is the typical output offset voltage and the corresponding input offset voltage. Here you have the circuit for measuring the input offset voltage.

(Refer Slide Time: 22:02)



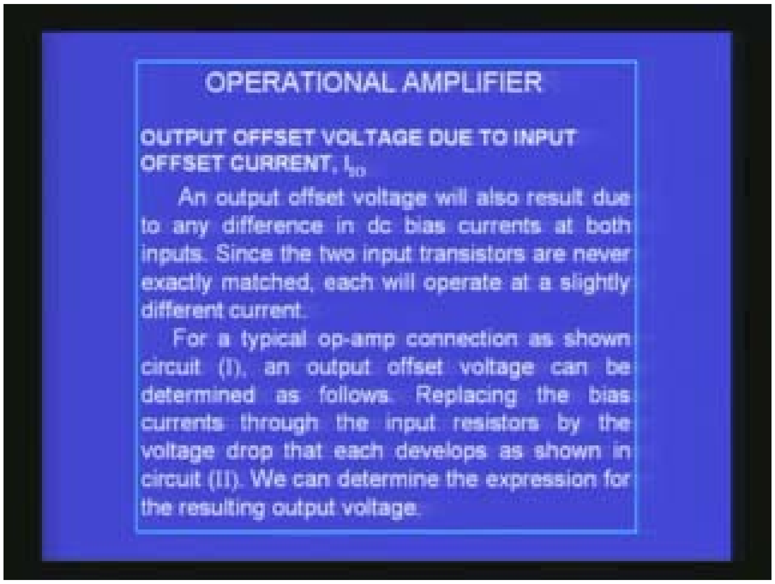
It is the same circuit which we used a moment ago. We have the 741 op amp. You have the R_f 1 megohm and R_1 100 kilo ohm and both the inputs are grounded. The same circuit is wired here on the bread board. You have the op amp, you have the two resistors and the wiring is done. This is the dual supply behind and the wiring is corresponding to the plus, minus and the ground are connected here and the pin number 6 is connected to the multimeter here which will measure the output voltage. The two input terminals are grounded and now let us see the reading in the multimeter.

(Refer Slide Time: 22:54)

The multimeter is in 200 millivolts range corresponding to this point; 200 millivolts range in that it is measuring 0.9 millivolt. That means the output offset voltage measured by the multimeter is 0.9 millivolt and the gain of the amplifier is 10 because this is 1 megohm and the feedback 100 kilo ohm. 1000 kilo ohm divided by 100 kilo ohm is approximately 10. If I now take 9 millivolts divided by 10 that gives 0.9 millivolt or 900 microvolt and that is the input offset voltage of this operational amplifier. All that you have to do is construct the amplifier measure the output voltage divide that by the gain and what you get is the input offset voltage. You saw how the input offset voltage can be measured in the laboratory for a given configuration by actually constructing an amplifier measuring the output voltage and then dividing by the gain you will be able to evaluate the input offset voltage. You can verify whatever value you get with the value the given by the manufacturer in the data manual.

I also mentioned to you that the output offset voltage has got two contributions. One that we have already seen is due to the finite input offset voltage and the second is due to the difference in the two bias currents at the two input terminals of the operational amplifier. We have to now find out what will be this offset current? We should first measure the bias currents in a given typical case and see whether the bias currents are equal or unequal. If they are unequal the difference in the two bias currents is what we call the input offset current.

(Refer Slide Time: 25:06)



OPERATIONAL AMPLIFIER

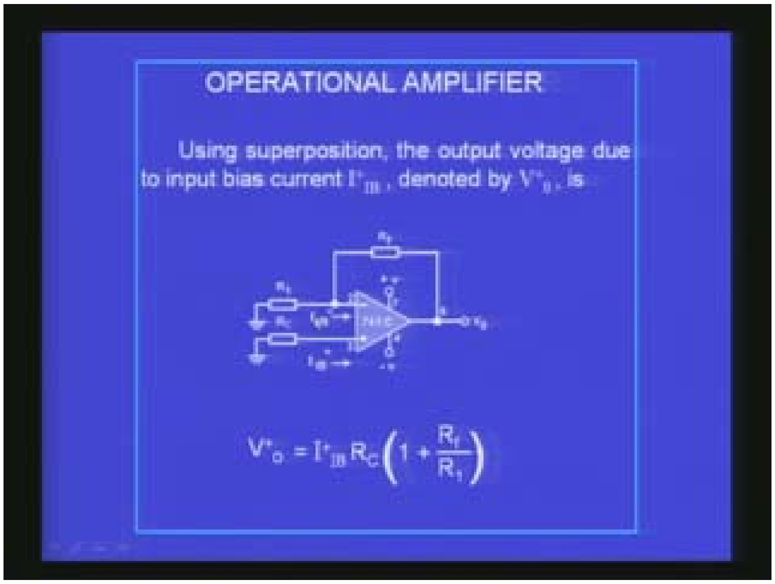
OUTPUT OFFSET VOLTAGE DUE TO INPUT OFFSET CURRENT, I_{IO}

An output offset voltage will also result due to any difference in dc bias currents at both inputs. Since the two input transistors are never exactly matched, each will operate at a slightly different current.

For a typical op-amp connection as shown circuit (I), an output offset voltage can be determined as follows. Replacing the bias currents through the input resistors by the voltage drop that each develops as shown in circuit (II). We can determine the expression for the resulting output voltage.

This input offset current flowing through the input resistance of the amplifier can also result in an output voltage which could be part of the output offset voltage. I have shown you another circuit on the screen. Again you have R_f, R_1 and R_c and I have shown the two bias currents flowing through the minus and the plus terminals of the operational amplifier 741 here as usual.

(Refer Slide Time: 25:38)



OPERATIONAL AMPLIFIER

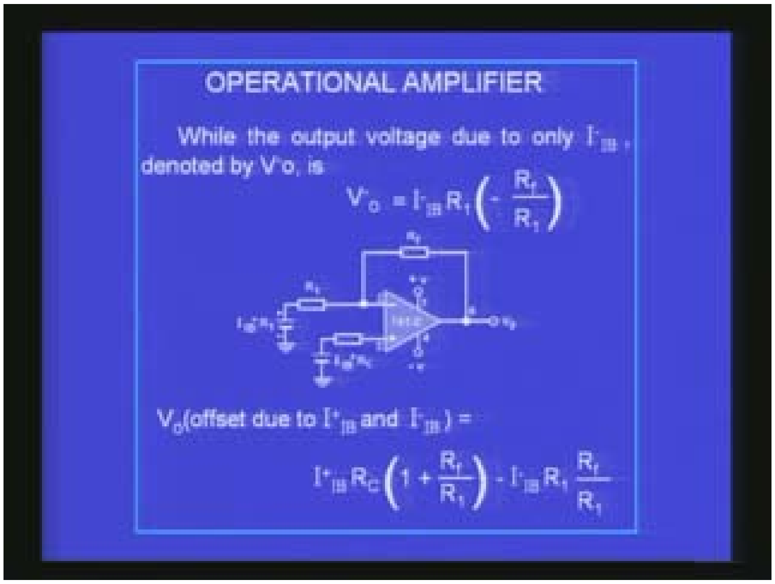
Using superposition, the output voltage due to input bias current I^+_{IB}, denoted by V^+_O, is

$$V^+_O = I^+_{IB} R_C \left(1 + \frac{R_f}{R_1}\right)$$

This bias current I call I_{1B}, I_{IB}; I is current this I is input B is for bias and I have put a minus here because this corresponds to the negative input terminal, the inverting terminal. Similarly I_{IB} plus corresponds to the input bias current flowing into the non-inverting terminal at the pin number 3 of the 741. What will be the output offset voltage due to these two currents is what I am trying to evaluate. I now apply the simple superposition theorem. Initially we assume that there is only one current flowing and find out what is the output voltage due to that current alone flowing without the other current. Then you bring in the other current assuming that the first current is non-existing and then calculate the output voltage. Then you perform an algebraic addition of these two voltages by superposition theorem. That gives you the total effective output voltage due to both the bias currents.

In the screen you see V_o plus that corresponds to only the I_B plus being present. The input bias current flowing into the non-inverting terminal alone is existing. If that current is flowing through a resistance R_c you would get a voltage I_{1B} into R_c. That voltage will be multiplied by the gain of the amplifier which is 1 plus R_f by R_1. This gives the output voltage due to only the input bias current flowing through the non-inverting terminal. What about the inverting terminal?

(Refer Slide Time: 27:34)



OPERATIONAL AMPLIFIER

While the output voltage due to only I^-_{IB}, denoted by V^-_o, is

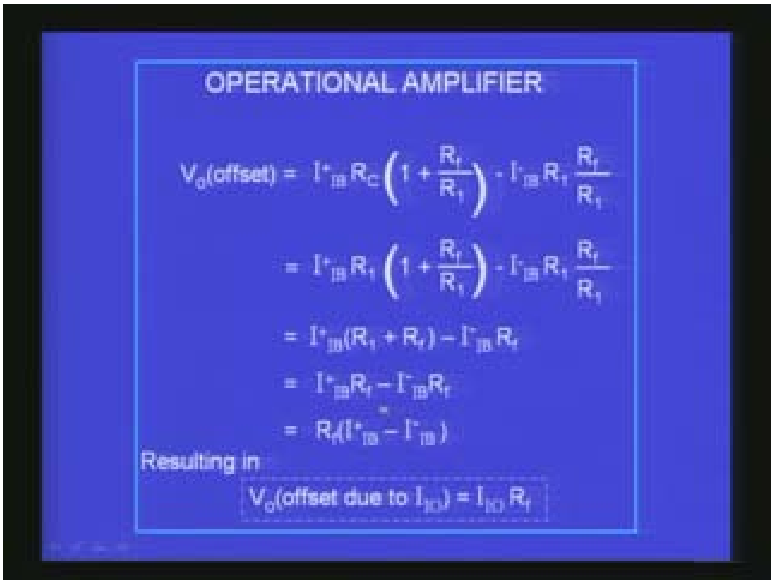
$$V^-_o = I^-_{IB} R_1 \left(- \frac{R_f}{R_1} \right)$$

V_o(offset due to I^+_{IB} and I^-_{IB}) =

$$I^+_{IB} R_C \left(1 + \frac{R_f}{R_1} \right) - I^-_{IB} R_1 \frac{R_f}{R_1}$$

If you want to look at the contribution due I_{IB} minus then that I call V_o minus. The voltage at the output is V_o minus due to this current and that is equal to I_{IB} minus into R_1 which is the voltage actually available at this point. The current into the resistance gives me the voltage multiplied by the gain of the amplifier. In that case you can see this is connected to ground. There is no input bias current here. We are considering only the bias current corresponding to the negative terminal or the inverting terminal. Then this is nothing but a simple inverting amplifier with the gain - R_f by R_1. That is why I have put here -R_f by R_1 is the gain factor. This is the voltage that will be developed across the R_1 due to the bias current flowing and so this is the output voltage due to this current. The total offset voltage due to the two currents I_{IB} plus and I_{IB} minus is nothing but the sum of the two terms that we already got. This is the first term I_{IB} plus into Rc multiplied by 1 plus R_f by R_1 minus this minus comes because there is a minus in the gain factor because it is a inverting amplifier; minus I_{IB} minus into R_1 multiplied by R_f by R_1. If you simplify that ultimately you will get an expression R_f multiplied by I_{IB} plus minus I_{IB} minus.

(Refer Slide Time: 29:10)



OPERATIONAL AMPLIFIER

$$V_0(\text{offset}) = I^{+}_{IB} R_C \left(1 + \frac{R_f}{R_1}\right) - I^{-}_{IB} R_1 \frac{R_f}{R_1}$$

$$= I^{+}_{IB} R_1 \left(1 + \frac{R_f}{R_1}\right) - I^{-}_{IB} R_1 \frac{R_f}{R_1}$$

$$= I^{+}_{IB}(R_1 + R_f) - I^{-}_{IB} R_f$$

$$= I^{+}_{IB} R_f - I^{-}_{IB} R_f$$

$$= R_f(I^{+}_{IB} - I^{-}_{IB})$$

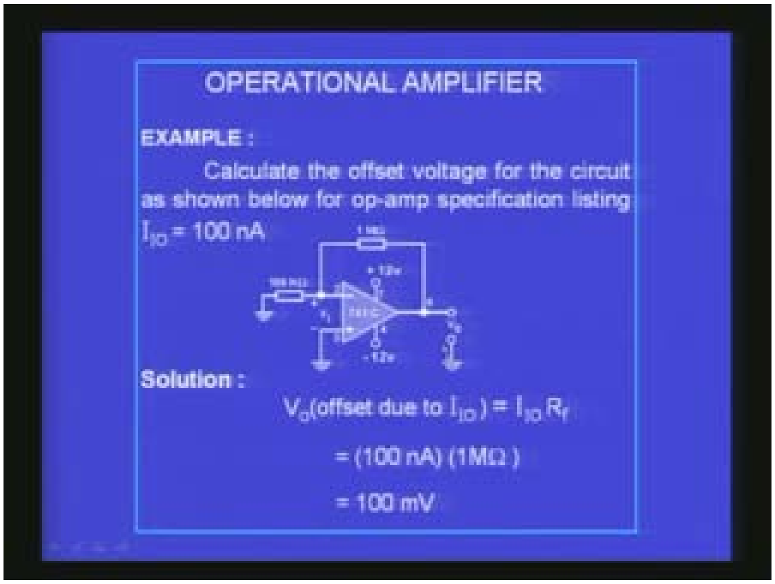
Resulting in

$$\boxed{V_0(\text{offset due to } I_{IO}) = I_{IO} R_f}$$

That shows the output offset voltage is basically due to the difference in the two bias currents. I_{IB} plus and I_{IB} minus, the difference multiplied by the feedback resistor R_f is responsible for the output offset voltage which also can be easily understood. This difference I_{IB} plus minus I_{IB} minus is what I call I_{IO}. That means the current at the input which is responsible for the offset. I_{IO} is nothing but the input offset current. The input offset current multiplied by R_f gives you the offset voltage due to the input bias current. After discussing the back ground, theory it is always useful to look at one simple illustration to understand the concept very clearly.

I have given an example here. Calculate the offset voltage for the circuit shown below for an op amp specification which lists input offset current to be 100 nano amperes. The current is a very, very small quantity 100 nano amperes. That is the difference between the two input bias currents. The input bias currents can be slightly higher than these but the difference is what they are giving as input offset current and that is 100 nano amperes. How do I calculate? The solution is output offset voltage due to the input offset current is nothing but input offset current multiplied by the feedback resistor because it becomes a current to voltage converter.

(Refer Slide Time: 30:50)



OPERATIONAL AMPLIFIER

EXAMPLE :

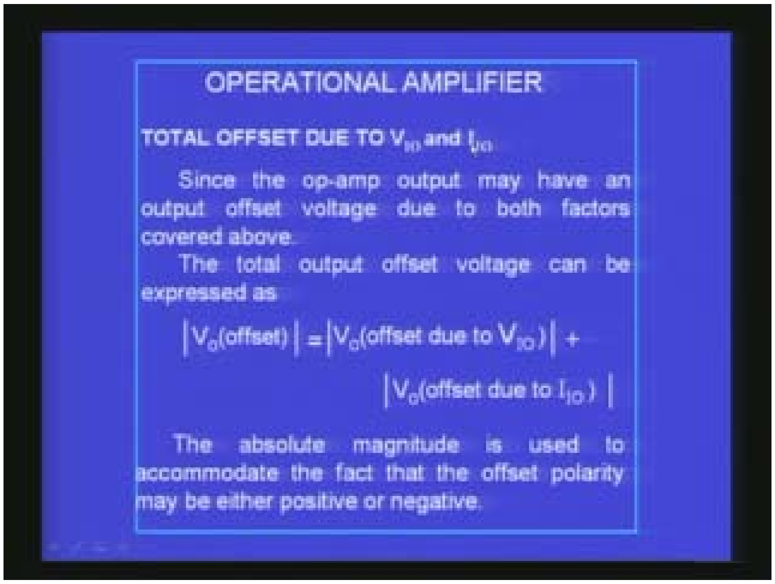
Calculate the offset voltage for the circuit as shown below for op-amp specification listing I_{IO} = 100 nA

Solution :

$$V_o(\text{offset due to } I_{IO}) = I_{IO} R_f$$
$$= (100\ \text{nA})\ (1\text{M}\Omega)$$
$$= 100\ \text{mV}$$

I_{IO} multiplied by R_f where R_f here is 1 megohm. 100 nano amperes multiplied by 1 megohm gives me 100 millivolt. The offset voltage due to the input bias current offset is 100 millivolt. This is a very, very simple way of calculating the output offset. What is the total offset due to both V_{IO} and I_{IO}?

(Refer Slide Time: 31:16)



OPERATIONAL AMPLIFIER

TOTAL OFFSET DUE TO V_{IO} and I_{IO}

Since the op-amp output may have an output offset voltage due to both factors covered above.

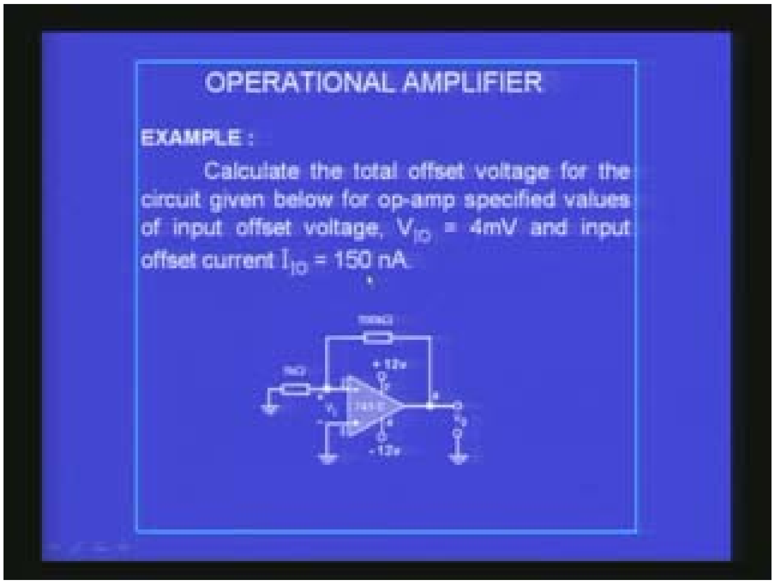
The total output offset voltage can be expressed as

$$|V_o(\text{offset})| = |V_o(\text{offset due to } V_{IO})| + |V_o(\text{offset due to } I_{IO})|$$

The absolute magnitude is used to accommodate the fact that the offset polarity may be either positive or negative.

You have to calculate V_{IO} calculate I_{IO} and then find out what is the voltage output due to V_{IO} and the voltage output due to I_{IO} only being present and then add them together algebraically. That gives you the total offset voltage. I have given again one more example where I we can calculate both of them together. Calculate the total offset voltage for the circuit given below for op amp specified values of input offset voltage V_{IO} 4 millivolts and the input offset current I_{IO} is 150 nano amperes.

(Refer Slide Time: 31:58)



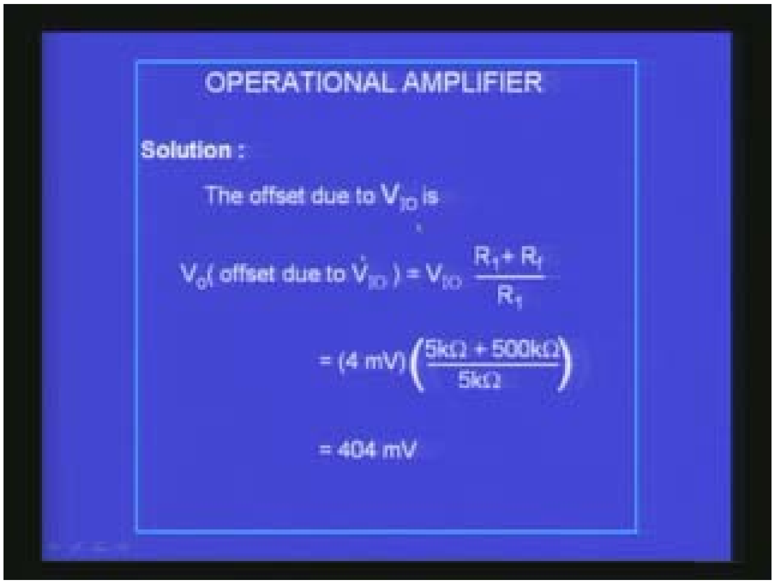
OPERATIONAL AMPLIFIER

EXAMPLE :

Calculate the total offset voltage for the circuit given below for op-amp specified values of input offset voltage, V_{IO} = 4mV and input offset current I_{IO} = 150 nA.

If somebody asks then you are in position to immediately calculate the total offset voltage because you know how to get from V_{IO} the output offset voltage. You also know how to calculate the output offset voltage using the I_{IO} the input offset current. Here the feedback resistor is 500 kilo ohm and R_1 is 5 kilo ohm. That is what you should remember. What is the offset voltage?

(Refer Slide Time: 32:25)



OPERATIONAL AMPLIFIER

Solution :

The offset due to V_{IO} is

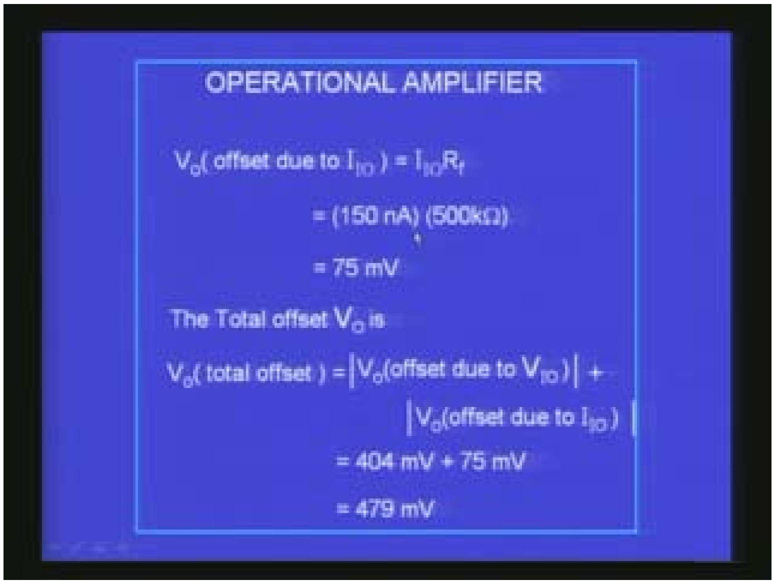
$$V_o(\text{ offset due to } V_{IO}) = V_{IO}\,\frac{R_1 + R_f}{R_1}$$

$$= (4\text{ mV})\left(\frac{5\text{k}\Omega + 500\text{k}\Omega}{5\text{k}\Omega}\right)$$

$$= 404\text{ mV}$$

The offset voltage due to V_{IO} is V_{IO} multiplied by the gain. The gain here is R_1 plus R_f by R_1 which is 5 kilo ohm plus 500 kilo ohm by 5 kilo ohm and when you multiply it is almost 101 and multiplied by 4 millivolts gives me 404 millivolts. This 4 millivolts is the input offset voltage given in the problem. You get 404 millivolts as the offset voltage due to input offset voltage alone. We also should calculate the contribution to the output offset voltage due to the input offset current I_{IO} and the formula is V_o or the output voltage offset due to input bias current is nothing but input current offset multiplied by R_f the feedback resistor.

(Refer Slide Time: 33:16)



OPERATIONAL AMPLIFIER

V_o(offset due to I_{IO}) = $I_{IO}R_f$

= (150 nA) (500kΩ)

= 75 mV

The Total offset V_o is

$$V_o(\text{total offset}) = |V_o(\text{offset due to } V_{IO})| + |V_o(\text{offset due to } I_{IO})|$$

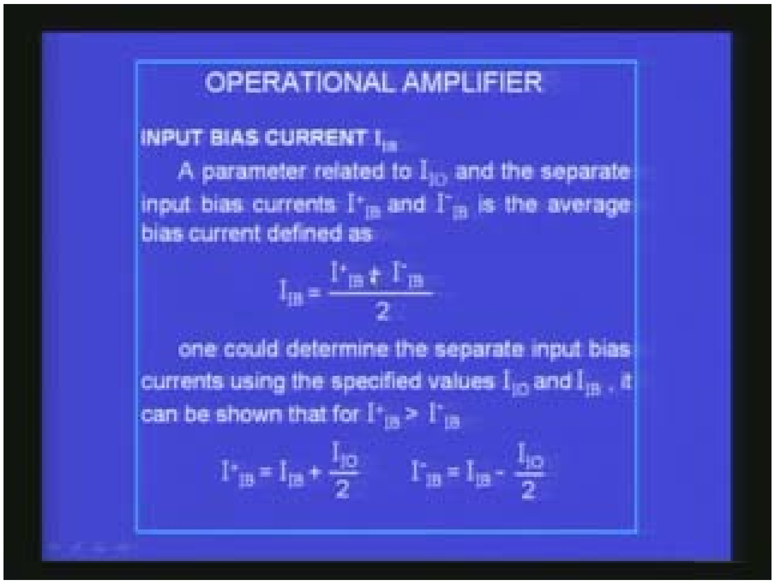
= 404 mV + 75 mV

= 479 mV

150 nano amperes is the value of the input offset current multiplied by 500 kilo ohm which is the value of the R_f and when you multiply you get 75 millivolts as the answer. You have now independently calculated the output offset voltage due to input offset voltage alone and due to input offset current alone. The total offset voltage is the sum of these two. Total is 404 millivolt due to input offset voltage plus 75 millivolts due to input offset current and the total is 479 millivolt which is the answer for the problem. By knowing very simple relationship between the output and the input in these cases one can actually measure input offset voltage, measure input bias currents also and then try to find the input bias current and calculate the contribution of the output offset voltage from these two sources.

We will move into the next stage and try to find out how to measure input bias current. It will be good to measure input bias current and the corresponding what is the current flowing into the positive terminal and the negative terminal at the input. How do you define the input bias current I_{IB}? I_{IB} plus and I_{IB} minus are the two bias currents flowing into the plus and the minus terminals of the amplifier. I_{IB} is the average of these two currents I_{IB} plus + I_{IB} minus divided by 2. We have already also seen that these two currents ideally should be equal but in reality they need not be equal and that is why we take the average of the two currents.

(Refer Slide Time: 35:19)



OPERATIONAL AMPLIFIER

INPUT BIAS CURRENT I_{IB}

A parameter related to I_{IO} and the separate input bias currents I^+_{IB} and I^-_{IB} is the average bias current defined as

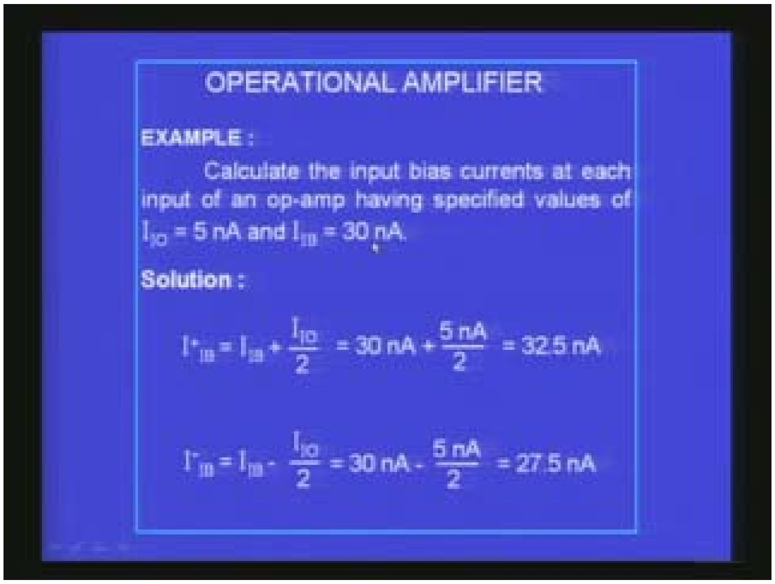
$$I_{IB} = \frac{I^+_{IB} + I^-_{IB}}{2}$$

one could determine the separate input bias currents using the specified values I_{IO} and I_{IB} , it can be shown that for $I^+_{IB} > I^-_{IB}$

$$I^+_{IB} = I_{IB} + \frac{I_{IO}}{2} \qquad I^-_{IB} = I_{IB} - \frac{I_{IO}}{2}$$

Once you know this you can also determine the separate input currents flowing into each of the terminals. From this equation you can obtain I_{IB} plus is nothing but I_{IB} plus I_{IO} by 2. If you know the input offset voltage and the input bias current you can actually calculate the input bias current through the plus terminal and the input current through the minus terminal. The input current through the minus terminal is again I_{IB} minus I_{IO} by 2. Let us try to do a simple illustrative problem. Calculate the input bias currents at each input of an op amp having specified values of input offset current I_{IO} 5 nano amperes and I_{IB} 30 nano amperes.

(Refer Slide Time: 36:12)



OPERATIONAL AMPLIFIER

EXAMPLE :

Calculate the input bias currents at each input of an op-amp having specified values of I_{IO} = 5 nA and I_{IB} = 30 nA.

Solution :

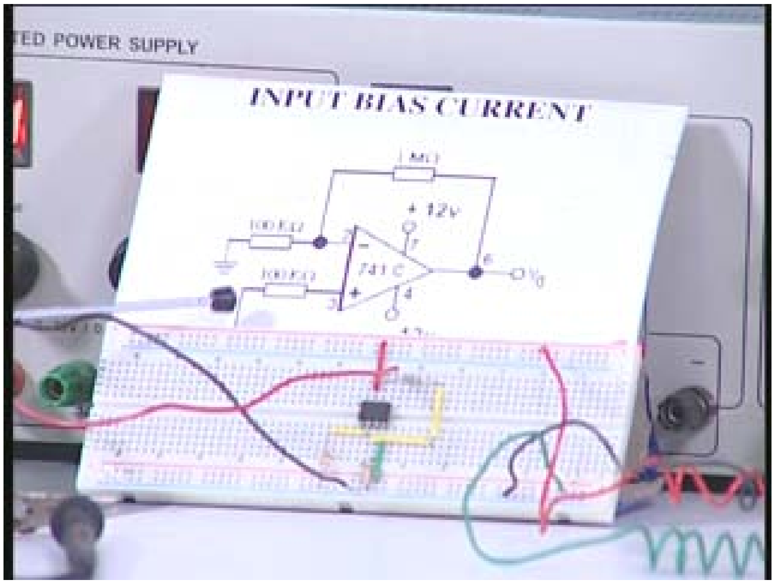
$$I^+_{IB} = I_{IB} + \frac{I_{IO}}{2} = 30\text{ nA} + \frac{5\text{ nA}}{2} = 32.5\text{ nA}$$

$$I^-_{IB} = I_{IB} - \frac{I_{IO}}{2} = 30\text{ nA} - \frac{5\text{ nA}}{2} = 27.5\text{ nA}$$

The average of the two input currents is 30 nano amperes and the difference is 5 nano amperes. I_{IB} plus is nothing but I_{IB} plus I_{IO} by 2. That is equal to 30 nano amperes plus 5 nano amperes by 2. That is 32.5 nano amperes and I_{IB} minus is with a negative sign here. That is 30 nano ampere minus 5 nano amperes by 2. That is 27.5 nano amperes. These two are the individual bias currents flowing into the two terminals and the average of this is 30 nano amperes which is the input bias current and the difference between these two is about 5 nano amperes that is the input offset current. If they give two and ask the third one it is very easy for us to calculate what the value is.

Let me go show you how to measure input bias currents. Here I have the operational amplifier circuit where I have again used 1 meg ohm for the feedback and 100 kilo ohm at the R_1 and I have also connected another 100 kilo ohm to the ground. The terminal three is connected to the ground.

(Refer Slide Time: 37:29)



I want to measure the input bias current flowing into this and the input bias flowing into the other plus terminal. These two input bias currents I want to know. The simplest method is to actually measure the output voltage and by using a multimeter you can measure the voltage here and the voltage at this pin; exactly at the pin number 2 with reference to ground and pin number 3 with reference to ground. The voltage divided by this resistance gives you the current. That is what I am going to now do. The corresponding op amp circuit is shown below in the bread board. You have the op amp and the different resistors are connected exactly in the same manner shown here and now what I am going to do is I am going to take the multimeter output and connect it to pin number 2 and measure the voltage at pin number 2. I have put it in millivolts; 200 millivolts range and the output on the voltage measured is -4.7. This is 4.7 millivolts. The voltage at pin number 2 is -4.7.

(Refer Slide Time: 38:47)

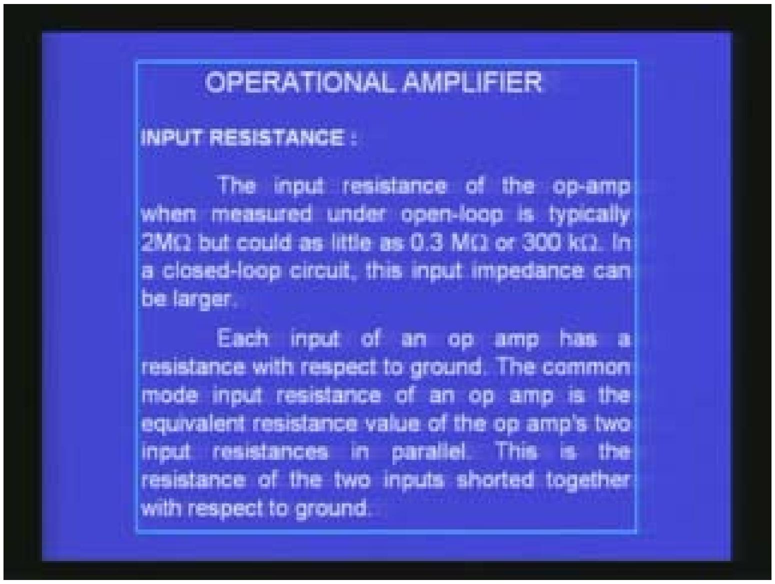
What is the input bias current? The input bias current is -4.7 divided by 100K. It is 0.047. That means 47 nano amperes is the current that is flowing into this. By knowing the voltage and the resistance we can calculate the input bias current. Now what I am going to do is I am going to remove the multimeter connection from pin number 2 and connect it to pin number 3. I remove it and connect it to pin number 3 and if you see the multimeter now the voltage is 3.7 millivolt. Again it is -3.7 millivolts and the input bias current corresponding to the non-inverting terminal pin number 3 is 3.7 millivolt divided by 100K which is again about 37 nano amperes.

(Refer Slide Time: 39:47)

You have about 37 and 47 nano amperes and the difference which is called the input bias current offset is 47-37. It is about 10 nano amperes. In the example that we saw it was about 5 nano amperes they have given. It is of the same order. It is about 10 nano amperes. That is the input offset current that we have. That means the difference in the current between the two terminals corresponding to inverting and non-inverting terminals. It is very easy to measure the input bias currents and if you want to know the input bias current you find the average of 47 and 37 nano amperes. That gives you the average input bias current and the input offset voltage is the difference. We can calculate the input bias currents and the bias current offset.

We will move on to the third characteristics of the op amp which is input resistance. We have also seen if you recall in one of the earlier lectures how to measure the input resistance and the output resistance of any amplifier, usually the transistor amplifier. I remember I also showed a demonstration of the actual measurement of input resistance of an amplifier. Usually not many people know about this in general. So it will be good to again go through this exercise and try to understand how to measure the input resistance of a given operational amplifier circuit. What do you mean by input resistance?

(Refer Slide Time: 41:28)



OPERATIONAL AMPLIFIER

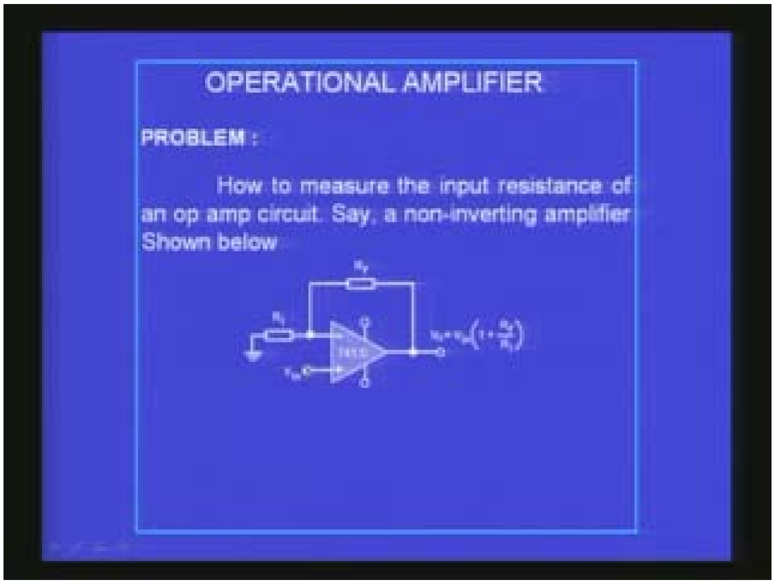
INPUT RESISTANCE :

The input resistance of the op-amp when measured under open-loop is typically 2MΩ but could as little as 0.3 MΩ or 300 kΩ. In a closed-loop circuit, this input impedance can be larger.

Each input of an op amp has a resistance with respect to ground. The common mode input resistance of an op amp is the equivalent resistance value of the op amp's two input resistances in parallel. This is the resistance of the two inputs shorted together with respect to ground.

Input resistance is input voltage divided by the input current in principle. The input resistance of an open loop configuration of an op amp is in the order of meg ohm. About 1 or 2 meg ohm will be the manufacturers specification and as a matter of fact it can differ from one operational amplifier to another. In general it will be a very, very large value. We all know that for a good voltage amplifier the input resistance should be very, very large. We have seen it many times in the earlier lectures also. How do you measure the input resistance of an op amp circuit say a non-inverting amplifier shown below. I have taken an example to explain to you how to measure the input resistance of a given configuration. What I have here is a non-inverting amplifier with R_f and R_i and the input is given at the pin number 3 or a non-inverting terminal.

(Refer Slide Time: 42:40)



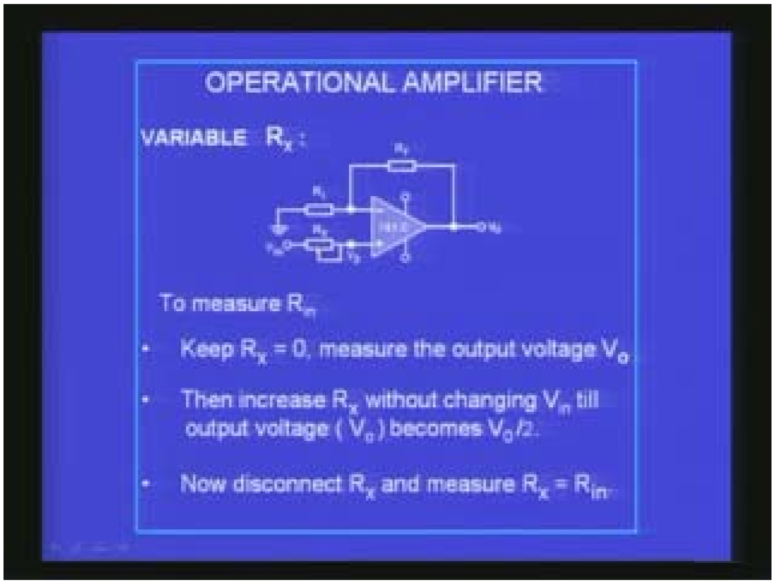
OPERATIONAL AMPLIFIER

PROBLEM :

How to measure the input resistance of an op amp circuit. Say, a non-inverting amplifier Shown below

The output voltage is equal to V_{in} multiplied by 1 plus R_f by R_i which is corresponding to the non-inverting amplifier. Now what I am going to do is I am going to add another resistor at the input which is a variable resistor of several megohms invariably it is a very high resistor. That is what is shown in this figure.

(Refer Slide Time: 43:09)



OPERATIONAL AMPLIFIER

VARIABLE R_x :

To measure R_{in}

- Keep $R_x = 0$, measure the output voltage V_o
- Then increase R_x without changing V_{in} till output voltage (V_o) becomes $V_o/2$.
- Now disconnect R_x and measure $R_x = R_{in}$

R_x is a variable resistor. It can go from 0 to a maximum value of 10 megohm or 1. If you have such a potentiometer or a variable resistor this experiment can be easily done. To measure R_{in} what you do is initially you keep R_x equal to 0. That means you are almost shorting this. There is no resistance here; zero resistance. V_{in} and V_3 are equal. Keep R_x

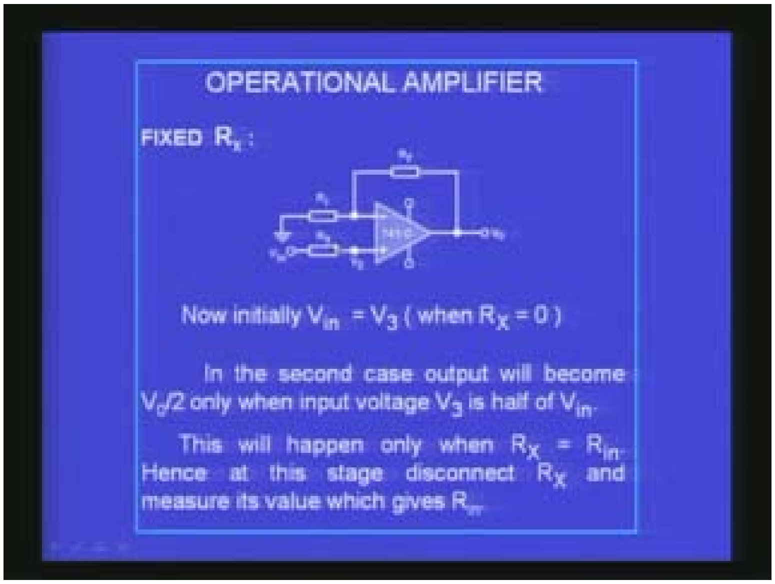
equal to 0 and measure the output voltage. The entire voltage is available at pin number 3 or at the non-inverting terminal and output voltage is now measured. Now what I do is I don't disturb the input voltage or any of the other components in the circuit. By using the variable potentiometer knob I keep increasing the resistance till I get an output voltage which is half of the previous value that I measured with R_x equal to 0. All that I do is I keep increasing the value of R_x till I get an output voltage which is half the previous value keeping the V_{in} constant. I don't change the V_{in} at all. Whatever is the input voltage it will be multiplied by the gain and I will get the output. If the output voltage has become half of the pervious value that means that V_3 has become half of V_{in}. The voltage at point V_3 has become half of the voltage at point V_m. That is what we understand when we get half the voltage.

When will this happen? When will a voltage divide equally? It will happen only if I have two resistors which are of equal value. If I have two 100K resistors connected to 5 volt if I measure the voltage across one of the resistors the voltage will be 2.5. A resistor is basically a linear device and the total voltage is split into half and each of the resistors drop equal values of voltages which is V/2. This will happen when the two resistors are equal. One resistor is an external resistor that I have deliberately connected as a potentiometer and the other resistor is an internal input resistance that is coming at the input terminal. If I measure V_0 by two at that time I disconnect my R_x from the circuit and measure using the multimeter the value of the resistor and that resistance is the resistance of the input resistance of the amplifier.

This is an indirect method of measuring the input resistance. This is called half deflection method; you would have done it in several other similar situations. When you want to measure the resistance of the galvanometer you cannot use a multimeter directly because multimeter has got a big battery inside and it will drive a large current and it will spoil the galvanometer. To measure the resistance of the galvanometer you will always have a finite current through them by adjusting very small voltage source and then you will introduce a resistance in the circuit till you get half the current and then you conclude that whatever resistance that you have now included in the circuit should be equal to the resistance of the galvanometer and that is the method of half deflection. You first apply a voltage with R_x equal to zero. Measure the output voltage and keeping the input voltage constant, only change the R_x. Increase the value of R_x till you get half the value of the output. You should not measure the value of R_x in the circuit because there will still be voltages coming at different points. Any measurement will have to be done in passive condition. That means you should remove the R_x. Preferably it is better to remove the R_x and then measure using a multimeter. Thereby you would be able to get the input resistance of the amplifier.

Due to various reasons usually the input resistance of an amplifier like non-inverting amplifier can be very very high. Sometimes 100 megohm, 50 megohm because the open loop gain is very large value. When you make the gain very small whatever is the difference between the actual gain and the open loop gain will be the factor by which the input resistance, the bandwidth, etc will be increased in the case of op amp due to the feedback configuration and usually the value of input resistance can be very, very large immeasurably large. In an actual laboratory condition it is very difficult to get very large value megohm variable resistor potentiometer. I am trying to suggest you a much simpler scheme by using the same principle. What I have done is now I have introduced a fixed resistor R_x here instead of variable resistor.

(Refer Slide Time: 48:47)



OPERATIONAL AMPLIFIER

FIXED R_x :

Now initially $V_{in} = V_3$ (when $R_X = 0$)

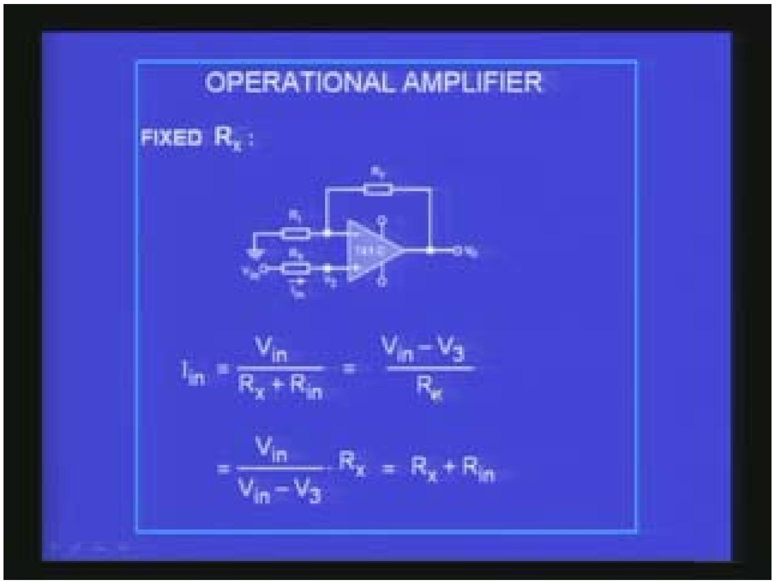
In the second case output will become $V_o/2$ only when input voltage V_3 is half of V_{in}.

This will happen only when $R_X = R_{in}$. Hence at this stage disconnect R_X and measure its value which gives R_{in}.

What I do is apply the input voltage directly to V_3. That means you eliminate R_x; keep R_x zero and measure the output voltage. After that we introduce this R_x and give the input at the input terminal of R_x and now measure the output voltage. You can actually trim the value of R_x by introducing different higher values of fixed resistors till you get half of the previous value. Instead of directly using a potentiometer you keep trying different values of resistors by increasing them in value till you get very close to half the value. But in principle you will not able to get a precise value of fixed resistors to get the exact value of the input resistor. We can also evaluate from the circuit what should be the input resistance if I measure an additional voltage which is V_3 in the circuit here. You measure V_{in}, V_3 and V_o. The R_x and R_{in} are in series and V_{in} is the total voltage applied. V_3 is the voltage at the mid point of these two resistors and if I know that I can calculate the actual ratio of the two resistors and if I know one of them I will know what R_{in} is. R_x I know because I only connect it in the circuit and since I know R_x I can evaluate the value of R_{in}. That is the scheme I am trying to explain to you.

In this circuit that you have got what is the current I_{in}? I_{in} is V_{in} divided by the total resistance. The total resistance is R_x plus the R_{in} which is the internal resistance in which we are interested. V_{in} divided by R_x plus the R_{in} is I_{in}. It is also equal to the difference between the two voltages at the end of R_x. V_{in} minus V_3 divided by R_x; change in voltage divided by resistance gives me the current through the resistor. This is also a simple expression of Ohm’s law.

(Refer Slide Time: 51:08)



OPERATIONAL AMPLIFIER

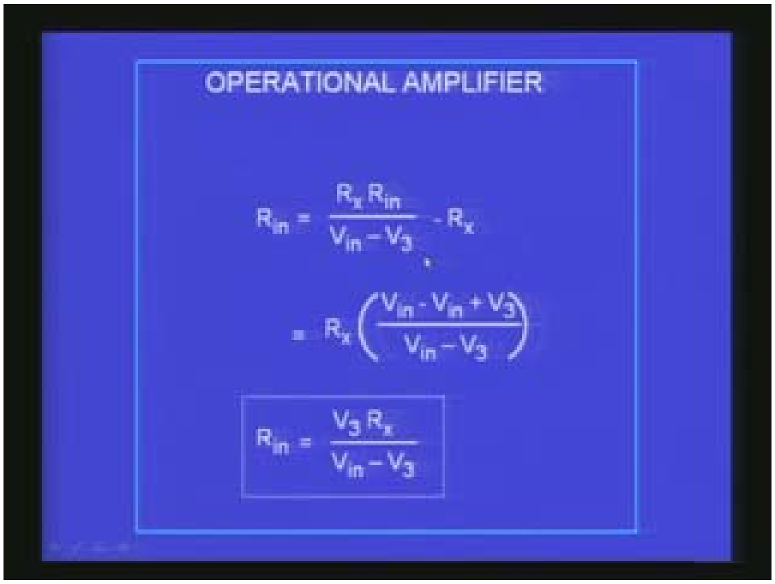
FIXED R_x :

$$I_{in} = \frac{V_{in}}{R_x + R_{in}} = \frac{V_{in} - V_3}{R_x}$$

$$= \frac{V_{in}}{V_{in} - V_3} \cdot R_x = R_x + R_{in}$$

If I now simplify this expression V_{in} by V_{in} minus V_3 into R_x by rearranging this equation that gives R_x plus R_{in} and R_{in} is R_x multiplied by R_{in} by V_{in} minus V_3 minus R_x.

(Refer Slide Time: 51:25)



OPERATIONAL AMPLIFIER

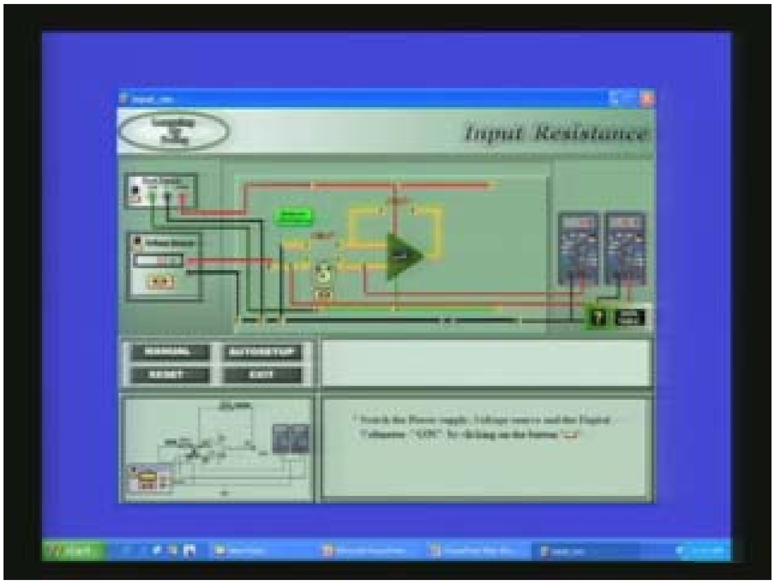
$$R_{in} = \frac{R_x R_{in}}{V_{in} - V_3} - R_x$$

$$= R_x \left(\frac{V_{in} - V_{in} + V_3}{V_{in} - V_3} \right)$$

$$\boxed{R_{in} = \frac{V_3 R_x}{V_{in} - V_3}}$$

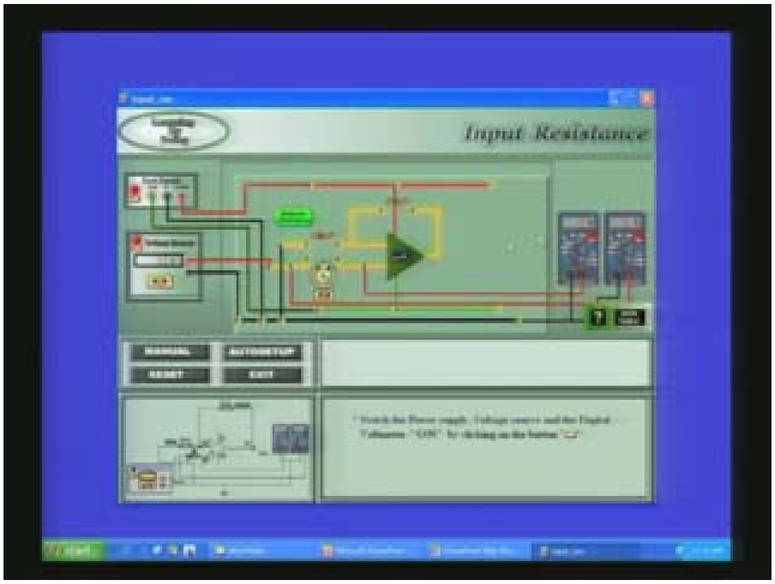
You can further simplify the mathematical expression and you can get R_{in} from V_3 into R_x by V_{in} minus V_3. All these quantities are known and you can measure them and calculate what is R_{in}? This is another thing that I wanted to show you. Before I actually go into that I want to show a simulation of the measurement. So you have here a board in which the op amp is sitting at the center. It is a printed circuit board in which the op amp is there and you have some gap which you can fill. I will now do auto setup. I have put a variable resistor here I have put a fixed resistor here. R_1; this is R_2 and the wiring is completed by using two multimeters, a dual supply and a voltage source, etc.

(Refer Slide Time: 52:25)



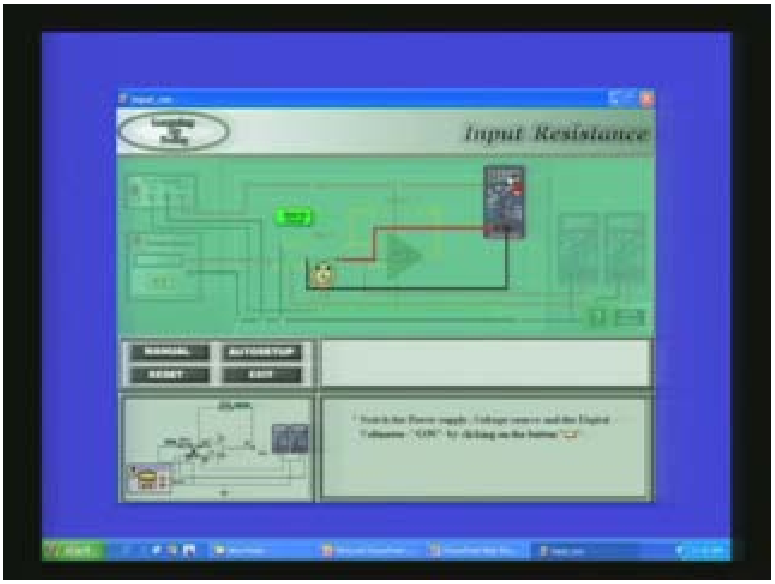
What is that I have to do? First keep the resistance zero. You can see the wiper is at this point. That means there is zero resistance here. With the zero resistance I will apply some voltage. I will switch on the power supply now; all the power supply and multimeters. Now I switch on let us say 1 volt. I have given 1 volt. The output voltage is 1 volt. Because both the resistors are 10K, 10K equal I am getting 1 volt. Now what I do is I will keep increasing the resistance till I get 0.5 volts across. Now it is 0.5 volts.

(Refer Slide Time: 53:14)



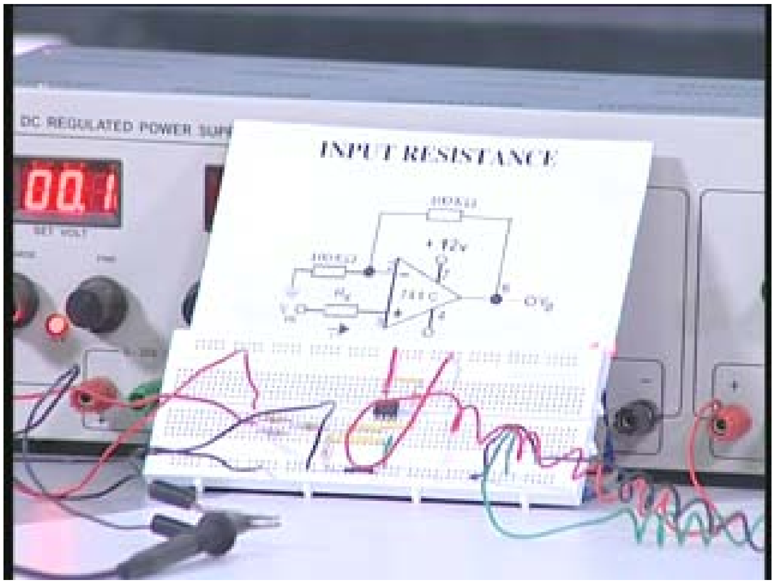
This multimeter measures the voltage at V_3. This multimeter measures the voltage at the input and when it is 0.5 volts then you know the value of the resistor that I have here in the variable resistor is the actual value of the internal resistance of the op amp. In order to measure I will go to measure the resistance. That is disconnected from the circuit and the resistance is measured using another multimeter and it shows around 5.1 megohm.

(Refer Slide Time: 53:47)



5.1 megohm is the input resistance by this half deflection method. That is what we have now measured. Having seen this let me quickly go and show you an actual measurement on the the laboratory table. Here I have a voltage source which actually is a millivolt source which we have used earlier also in many of our demonstrations. This is a millivolt source and the millivolt source is connected at the input of this amplifier which is the same amplifier which I have shown you just now. Instead of 10K I have used 100K here. They are equal value and I give the input voltage here from the millivolt source and I measure the output voltage and then I introduce the R_x here of an appropriate value so that the output is near about half the value. If that happens then R_x should be equal to R_{in}. That is the principle.

(Refer Slide Time: 54:50)



Now I get about 0.495 volts which is in 2 volts range and 0.495 or nearly 0.5 volts is the voltage that I measure at the input.

(Refer Slide Time: 55:06)

That means this gives around 500 millivolts or about 0.5 volts. Now I take it out and connect this at pin number 6 and find out the output voltage. The output voltage is - 400; about 400 millivolts when I give the input at this point after the resistor. What I do is I will take the input and give it at pin number 3. I have actually given the input at this point at pin number 3 directly. I have given the input from the millivolt source at this point pin number 3 and I measure the output voltage using the multimeter. It is about 1 volt; 0.99 volt.

(Refer Slide Time: 56:17)

Now what I do is I remove this input and connect it at the input point before the resistor. From here I disconnect the input voltage and connect it here. What you get? You get about half of that 0.573.

(Refer Slide Time: 56:34)

It is not exactly half but very close to half and that shows that whatever resistor I have connected here is approximately equivalent to the input resistance. Actually if you look at this, this is about 4.7 megohm and this is less than about 100 kilo ohms. So it is about 4.6 megohm. 4.6 megohm is very close to the input resistance of this configuration because when I connect it at the pin number 3 I get about 1 volt. When I connect it at this point I get about 0.5 volts and it is half of the previous value and this resistance that I have now introduced should be equivalent to the input resistance of the op amp. By this you will be in a position to measure the input resistance of any amplifier by using this principle.

We saw three different characteristics of the operational amplifier. The input offset voltage, input bias current and input resistance and also how they can be measured actually in a laboratory by using the different configurations. Thank you!