Basic Electronics

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Lecture- 28

Characteristics of Operation Amplifier
(Output Resistance, CMMR...)

In our series of lectures on basic electronics learning by doing we move on to the next. Before we do that let us recapitulate what we discussed during the previous lecture. You might recall that we started discussing the various characteristics of an operational amplifier. I listed also the different characteristics which are of importance in using the operational amplifiers for different applications.

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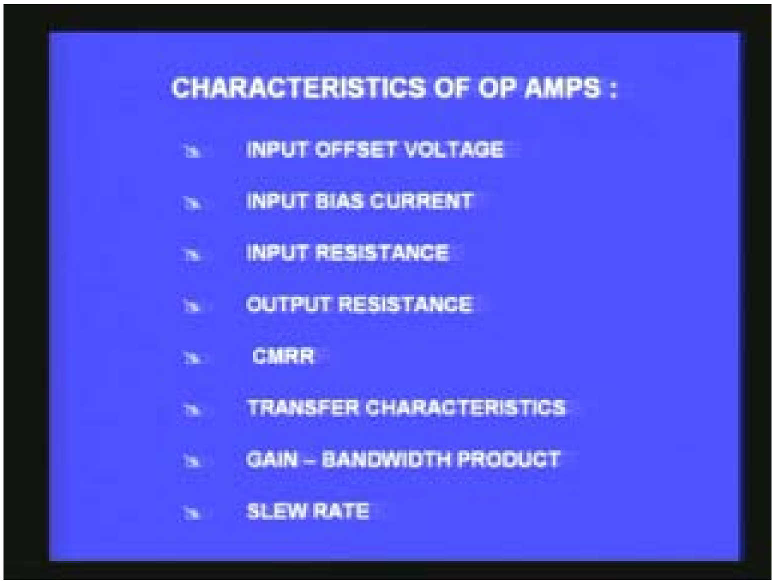

You can see the input offset voltage, input bias current, input resistance, output resistance, common mode rejection ratio what is known as CMRR; then there is transfer characteristics, gain-bandwidth product, slew rate are some of the important characteristics we have listed. If you recall the previous lecture you might remember that we discussed what we mean by the input offset voltage, the definition of the characteristics and how to measure the input offset voltage and then the input bias current the input bias current offset and also we saw what is the meaning of the input resistance and how to measure the input resistance for a given configuration.

Now we will move on to the other characteristics. Both the definition and how to measure them in a typical situation and I will try to show you also demonstration of how to measure these things in a laboratory. Before I do that I thought I would give you a table of data corresponding to an ideal operational amplifier and a typical operational amplifier where I have taken the example of 741 which is the most popular of the operational amplifiers.

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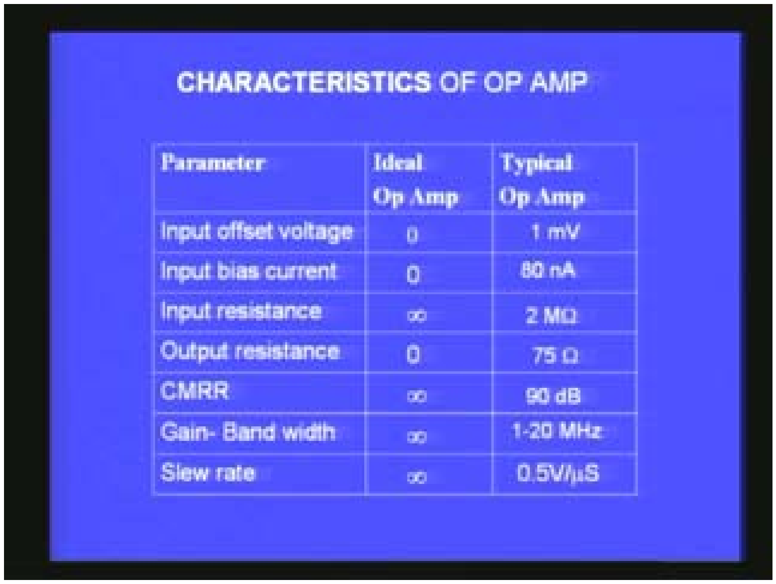
CHARACTERISTICS OF OP AMP

Parameter	Ideal Op Amp	Typical Op Amp
Input offset voltage	0	1 mV
Input bias current	0	80 nA
Input resistance	∞	2 MΩ
Output resistance	0	75 Ω
CMRR	∞	90 dB
Gain- Band width	∞	1-20 MHz
Slew rate	∞	0.5V/μS

If you look at for example the input offset voltage, ideally the offset voltage should be zero. You know by now that the input offset voltage is the voltage which I should provide at the input to make the output become zero when there are no more signals applied. In principle ideally the input offset voltage should be zero. But in typical 741 operational amplifier from the data table given by the manufacturer data sheet this value could be somewhere of few millivolts. In this case I have listed the typical 1 millivolt value which is given by the manufacturer data book. Similarly input bias current in principle should be zero but in real situation it cannot be zero because the input terminals correspond to the terminals of the base of the two transistors which form the differential amplifier configuration and the amplifier if you want it to work like an amplifier should have some minimum, low, finite current flowing through the base terminals of the transistors. It is impossible to have a zero bias current even though we list it as zero in the ideal case. In actual case it will be around few nano amperes. In this case in a 741 it is 80 nano amperes.

Incidentally you can also buy special purpose operational amplifiers which can have this input bias current a very, very low value of the order of pico amperes or even femto amperes. Pico ampere corresponds to 10 power -12 of an ampere or femto ampere 10 power -15 ampere. You can choose a very, very low bias current operational amplifier for special applications. But in a typical 741 case it is around 80 nano amperes. Nano means 10 power -9 of an ampere and it is a very, very small value for all practical purposes. Then if you look at the input resistance you can see ideally the input resistance of a voltage amplifier should be infinity; we have seen it several times so that the input source will not be loaded by the amplifier. The input resistance of good voltage amplifier should be infinity and that is why the infinity is listed under the ideal op amp situation. But if you look at the situation corresponding to 741 the input resistance is around 2 megohm; 10 power 6 is megohm. 2 into 10 power 6 ohms is typical value of the input resistance in the case of operational amplifier 741.

Now output resistance if you look at, it has to be zero because the output of a good voltage amplifier should be almost like an ideal voltage source. But if you look at the typical situation corresponding to the 741 it is 75 ohms which is rather low, very low. It is not zero but still it is a very small value of the order of 75 to 100 ohms. Similarly CMRR the common mode rejection ratio, about which I will explain to you in detail this time, should be around infinity whereas typically it is about 90 db. The db corresponds to decibel. We have also discussed how to look at that. 80 db is about 10,000. So 90 db is little more than 10,000. Similarly the gain-bandwidth should be infinity. That means the amplifier should be able to amplify all signals from very low level almost dc zero frequency to very infinite frequencies. But in principle it is not possible even in an actual case and in the case of operational amplifier this gain-bandwidth product will be about 10 power 6 or close to that. That is what is shown in the table. Last is the slew rate about which also we will discuss later. It is about 0.5 volts per microsecond in the case of the operational amplifier 741. This I want to give you so that you get an idea of the numbers corresponding to the various parameters and the characteristics that we talked about.

Let us move on to the next characteristic which we want to discuss in detail and that is the output resistance of the amplifier. What is the output resistance of the amplifier? For any amplifier we have already also measured this when we discussed transistor amplifier you might recall.

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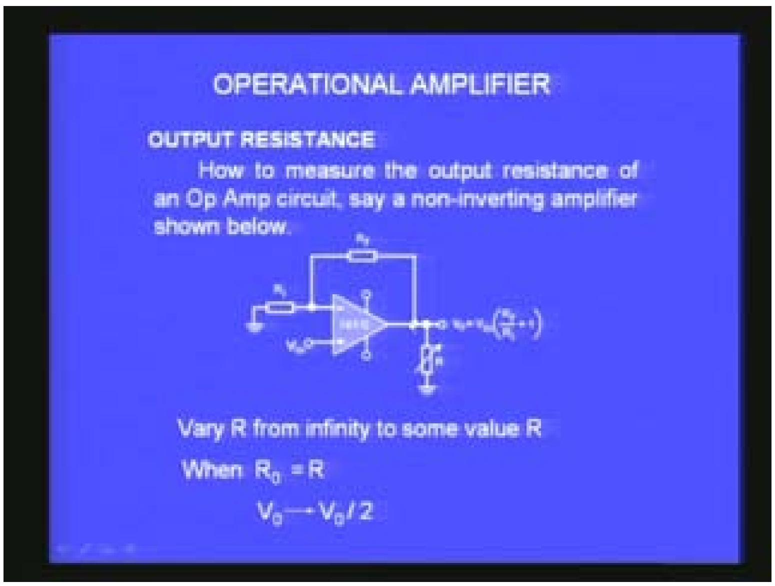

The output resistance is the resistance as you look from the output terminals into the amplifier. When you look from the output terminals what would be the resistance measured; the Thevenin's equivalent resistance and that is what is called output resistance. To measure the output resistance what do we do? What we do is we take one typical amplifier configuration. You can see on the screen it is a non-inverting amplifier. You have the R_f and the R_i and the R_i is grounded here and the input is applied at the non-inverting input and the output V output is equal to V_{in} into R_f by R_1 plus 1; 1 plus R_f by R_1. This is the gain factor. This is a very simple non-inverting amplifier about which we have already discussed. What I do is I connect a resistance between the output terminal and the ground. That is what I call R and the arrow shows that it is a variable resistance. That means the value of this resistance can be varied from zero value to some maximum value.

Now what I do is initially I disconnect this resistance. That means I make this R infinite. When I disconnect this it becomes infinite resistance and now I measure what is the output voltage? Then what I do is I introduce this resistance and vary the value of the resistance by using the potentiometer till I get a voltage which is half of what I measure with no resistance present here; that means with infinite resistance. If I get half of that value then the value of the R that I measured here now is the output resistance of the amplifier. This similar situation we have already discussed with reference to the input resistance in the last lecture. I would perhaps try to explain to you in simple terms why is it so. If you go on to the equivalent resistance of an operational amplifier between the two input terminals you have the resistance which is called the input resistance which we measured last time.

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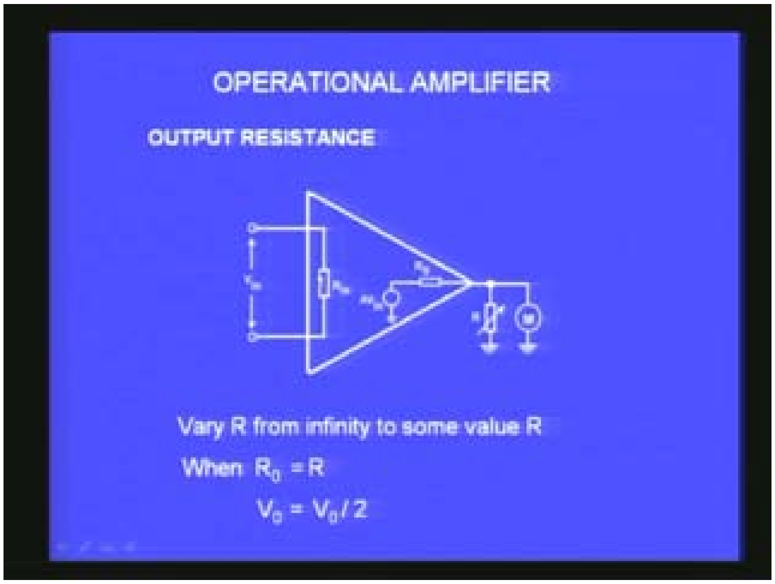

On the output side what you have is a voltage source which is actually having a value of A into V_{in} where V_{in} is the voltage that is impressed between the two input terminals. A is the voltage gain. In this case if no feedback is there it becomes A_{ol}, the gain with open loop condition. If you have a specific configuration corresponding to non-inverting or inverting then you can have a finite value of the gain depending upon the choice of resistances in the circuit. Whatever it is the output can be given as a voltage source A times V_{in} in series with an output resistance R_o.

Now look at the circuit with the external resistance connected. Without this resistance if you measure the voltage using the multimeter 'm' you will get V_0. After measuring that V_0 I introduce this resistance and I start varying this till I get V_0 exactly half of the previous value without altering any of the other input voltage or resistance, etc. When that happens, you can see from the equivalent circuit, the voltage source is now connected in series to two resistors R_o and R which is connected outside. If this R is not present I get V_o which is the actual value of the AV_{in}, the total voltage of the voltage source. The moment I connect the R here I do get a potential divider R_o and R form a potential divider and this voltage will have to be now divided between the two resistors R_o and R. What I measure in the multimeter will be the voltage that is obtained across the variable resistor R. When will this voltage become half of the applied voltage? It will become half only when R_o is equal to R. That is the principle of this measurement. I keep on varying this till I get half the value of the voltage that I measure previously and at that time I disconnect. That is very important. I disconnect this resistance and I measure its value using a good multimeter and that value will be the output resistance of the operational amplifier. This is the principle of measurement of output resistance.

Here you should also remember, I should caution, I have assumed that this voltmeter which measures the output voltage has got infinite resistance or R is very large resistance compared to the resistance that I have in the circuit. In this case the output resistance in general will be a very small value. I already mentioned to you that in the table the typical value for 741 is 75 ohms and this multimeter generally if it is digital multimeter for example it will have a very high input resistance of the order of several megohms and 75 ohms when it is in parallel to a large value of resistance this is as good as 75 ohms. That value will not be affected by the resistance of the multimeter. But if use any cheap multimeter which is not very well designed you have to take care that it will have its own resistance and that will come in parallel with R and it can lead to erroneous value and you have to be careful and use a high impedance voltmeter whenever you do these experiments. R_0 is equal to R when the output voltage is half of the previous value that I measured is the principle of the output resistance measurements.

I will quickly show you a simulation of the same where you can see I have the operational amplifier IC 741 at the center. I hope you are able to see that and there is a simple configuration. I have a dual power supply and I also have a voltage source and I have two multimeters to measure the input and output voltage. I press on the auto setup. Then various components will go and sit on their own and the circuit will be completed. What do you have here? You have an op amp; this is around 10K and this is also 10K. I have R_f 10K, R_i also 10K and that is connected to the ground and the voltage from the voltage source is connected to the non-inverting input here and it is a non-inverting amplifier with a gain 1 plus R_f by R_i and the R_f by R_i is equal to 1 here. It is a gain of 2; 1+1 = 2 is the gain of this amplifier. I always have large resistance here. This is a potentiometer and this is having very large resistance.

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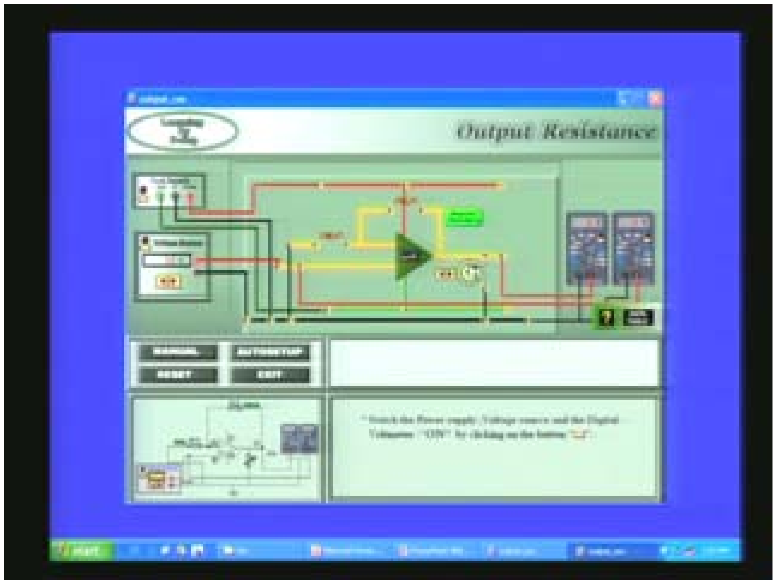

Let me switch on the power supply dual power supply, the voltage source, the multimeters and I will apply about 1 volt. I have applied 1 volt from the voltage source at the input and the output is around 1 volt. Now what I am going to do is I am going to vary this variable potentiometer slowly and you see what happens to the output voltage which is measured here. You find the output voltage is now 0.5.

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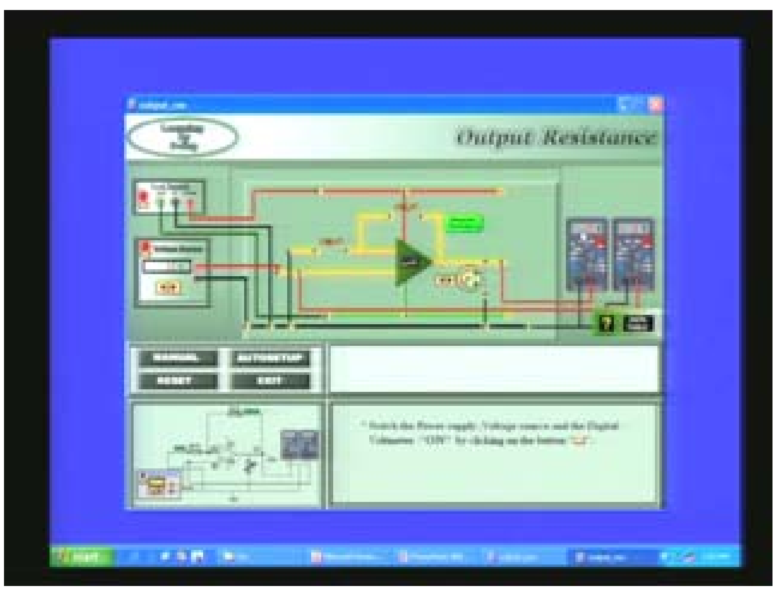

Previously the measured voltage was 1 volt and now it is 0.5 volt. That means it has become $V_0/2$. The output voltage is half of the input voltage and at that time I should know what the resistance is that I have included in the circuit in the variable resistor. For that I have to disconnect this resistor and I should make the voltmeter into a resistance meter, ohmmeter and measure at the terminals of this after disconnecting from the circuit. That is what I am going to do by pressing measure resistance. All the other things have been removed from the screen. Only the potentiometer is there and the two terminals of the potentiometer are connected to the voltmeter which is now measuring the ohms and you see a reading of 80 ohms.

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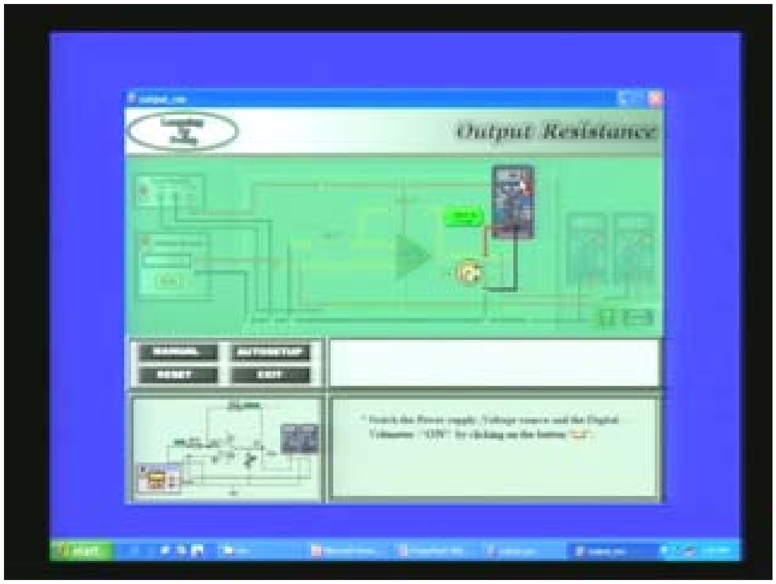

That gives us the output resistance of the operational amplifier. Having shown the simulation I would like to show you an actual measurement done on the laboratory table. Here you can see the circuit diagram shown on the top and there is a bread board at the bottom. In the circuit diagram we have used 10 kilo ohm as R_i and 100 kilo ohm as R_f and there is a gain of 1 plus 100 by 10; approximately 11 and the input voltage is given at the non-inverting input because it is a non-inverting amplifier and I have connected a potentiometer I will measure. I have not connected the potentiometer it is still here.

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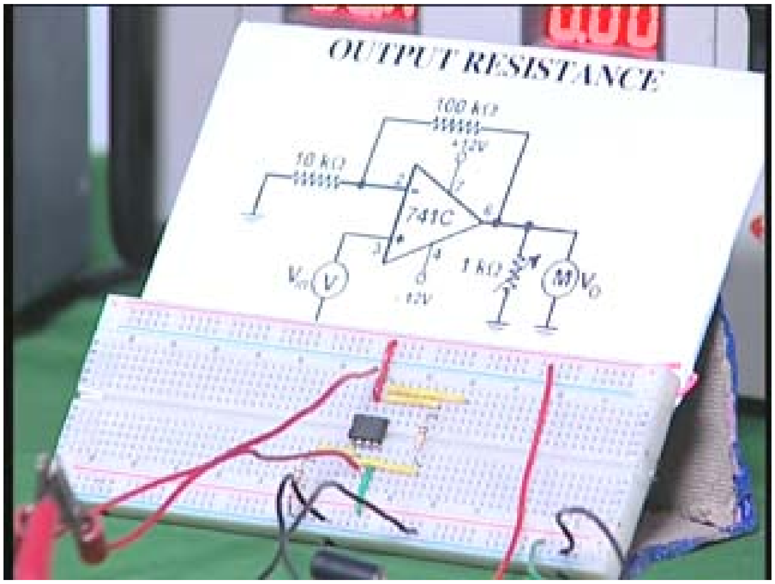

I will switch on the multimeter. I have given 200 millivolt from the voltage source. This is the voltage source you are now familiar with. We have seen it several times. This 200 millivolts input is given at the pin number 3 corresponding to the non-inverting input and the output is measured using the multimeter at pin number 6 and if you look at the multimeter it shows the value of 2.18.

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200 millivolt multiplied approximately by 10 is 2 volts. 2.18 is what I get. Without disturbing any of the voltages I should now connect the variable resistor which is here. This is the variable resistor. It is actually a 10 turn potentiometer. Usually in a normal

potentiometer if you just rotate by nearly 360 degrees all the resistance variation would have been made. In this case you have to rotate 10 times the spindle to make the variation possible for the whole range and you can do it in much smaller increments of resistance. That is why I am using it. Now I am going to connect this quickly into the output terminal. I have now connected the potentiometer and if I vary that the output voltage in the voltmeter is changing. You observe the output as I keep changing. You can see the voltage is increasing; now it is decreasing.

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It is 1.85 and it is still decreasing. I keep on increasing the voltage slowly and when it comes to about 1 volt I will stop. It is now 1.34; it is 1.1. It is about 1.02. Now I will stop. Previously it is about 2.18. So may be I can make it 1.09 or 1.07; 1.08. Now it is half the value that I measured previously 1.08.

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At this stage I should disconnect this resistance. I will connect it to a different area in the bread board and I also change the meter to measure resistance. I have converted the voltmeter into a resistance meter. There is 200 ohms range and I am now measuring the resistance by disconnecting from the circuit putting into an independent area and then I measure the value of the resistance is 49.8 nearly 50 ohms.

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That 50 ohms is the output resistance of this 741 that I have used in the circuit. In a typical table you saw the value should be around 75 ohms and 50 is actually a good value.

Having seeing how to measure the output resistance of an operational amplifier by actually performing an experiment let us move on to the next characteristics in the table and that is what is known as common mode rejection ratio or CMRR. It is called CMRR. This common mode rejection ratio is actually an important characteristics of differential amplifier. In any differential amplifier this parameter becomes an important one. Before we go into the actual definition of CMRR it will be good to know how a differential amplifier can be considered in two different modes corresponding to differential mode and common mode. If I now apply a signal between the two input terminals then this becomes the differential signal which is being applied to the operational amplifier. This is called a differential mode of connection.

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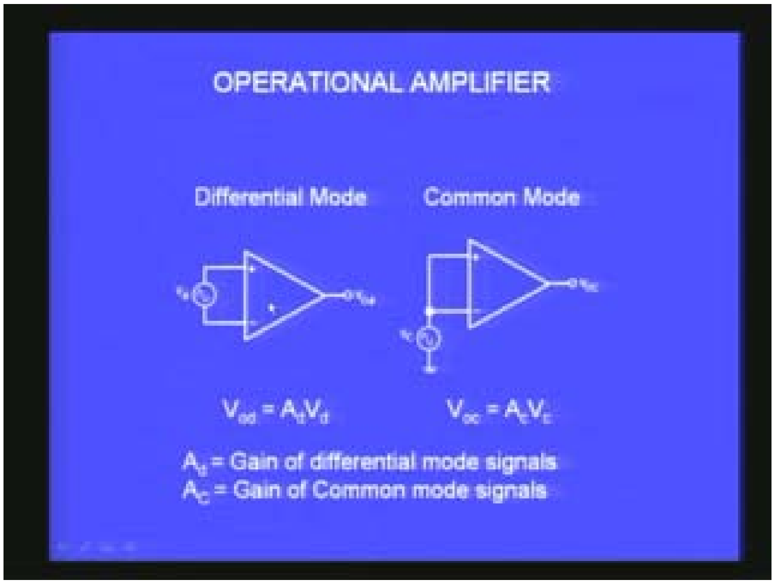

Instead if I connect the two inputs together shorting them and then apply a voltage between the ground and the point then this signal becomes common to both the input terminal and it is called common mode. This is the differential mode of connection this is the common mode of connection. In the differential mode of connection V_{od} that is the differential output voltage is equal to A_d which is called the differential gain into V_d the input differential voltage you apply at the differential mode. V_{od} is equal to A_d into V_d is corresponding to this configuration. Similarly for the common mode V_{oc} the voltage output corresponding to the common mode configuration is equal to A_c the common mode gain multiplied by V_c the common mode voltage applied at the input. We now talk of two different gains. One is called A_d the differential gain and the other is called A_c the common mode gain. In principle a differential amplifier can be associated with two different gains corresponding to A_d and A_c.

But in actual practice you would be giving to the two input terminals of an operational amplifier typically one voltage source corresponding to V_{i1} and another voltage source corresponding to V_{i2} independently without either connecting them together or connecting the voltage source between them.

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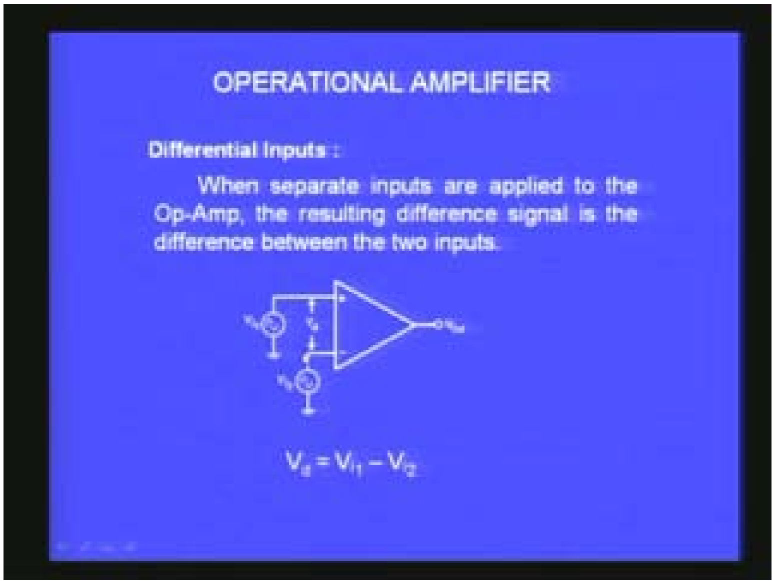

In that case how do we obtain the V_d and the V_c, the differential input voltage and the common mode input voltage. If V_{i1} and V_{i2} are the two input voltages V_d is nothing but the difference between the two; V_{i1} difference V_{i2}. Depending upon which is larger you will get either a positive or a negative value here. This can be the way which is the most practical way of looking at V_d and similarly for V_c for the same situation where I have applied V_{i1} for one terminal V_{i2} for other terminal V_c common mode will be given by the average of these two which is common for both the input; half of V_{i1} plus V_{i2}.

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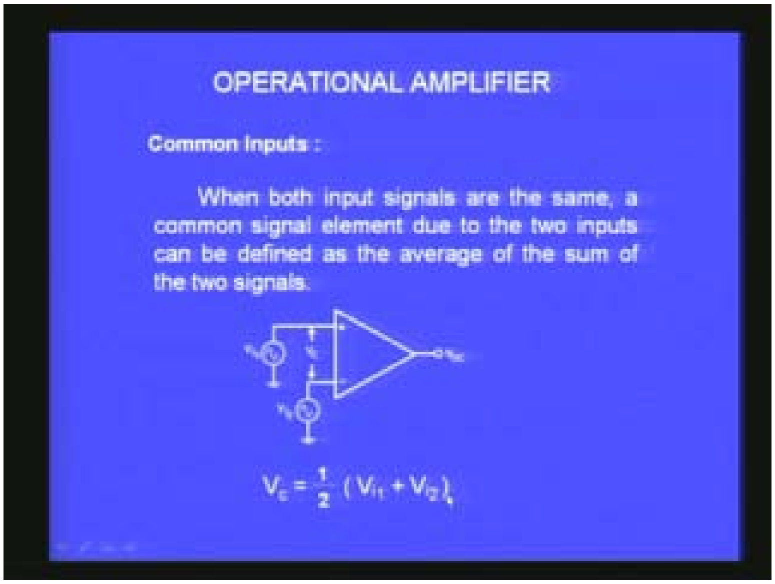

Now that we know there are two different modes, there are two different gains that one can talk of and how to obtain from the two independent voltages that you connect at the input terminals of an operational amplifier the V_c and the V_d?

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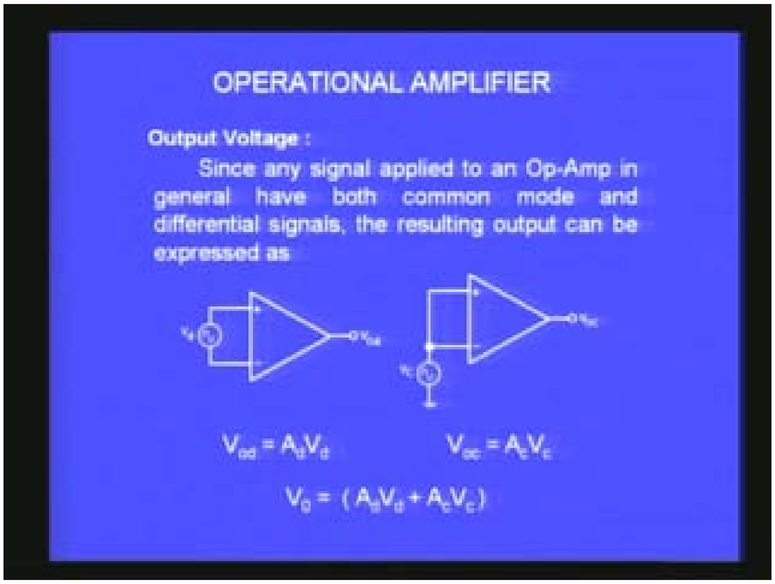

Having got that now you can see what is the total output in principle? This whenever you connect at the input V_{i1} and V_{i2} output will be V_o but that output voltage will have contributions from the common mode voltage as well as the differential voltage. V output in principle is the combination of A_d into V_d, where V_d is the differential voltage and A_c into V_c where V_c is the common mode voltage and A_d and A_c are the differential and common mode gains. This is the general expression for the output of a differential amplifier and A_d and A_c are the differential and common mode gains.

Having explained about all these things it will very easy to define now the common mode rejection ratio which is actually defined by the differential voltage gain divided by the common mode voltage gain. What does it say, CMRR? It tells you how much is the differential voltage gain larger than the common mode gain? The value of the CMRR is normally expressed in decibels using logarithmic. As definition CMRR log is equal to 20 log to base 10 A_d by A_c in decibels. For example typically for 741 this CMRR is 90 db. I already mentioned to you and also showed you in the table at the beginning of the lecture. That 90 db corresponds to nearly 10,000; little more than 10,000 and that means what? The differential gain will be 10,000 times the common mode gain.

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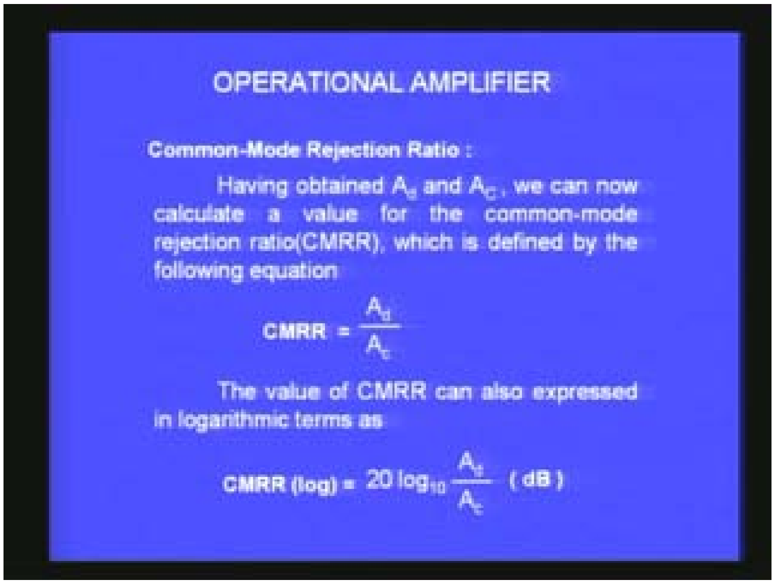

The ratio is 10,000. That means the operational amplifier has got some special preference for differential gains than the common mode gain. It does not give importance to the common signal but it gives importance only to the differential. This a very, very important characteristic as I already mentioned to you because most of the time for every amplifier whenever I use in any situation there is always enormous sources of noise voltages all around us.

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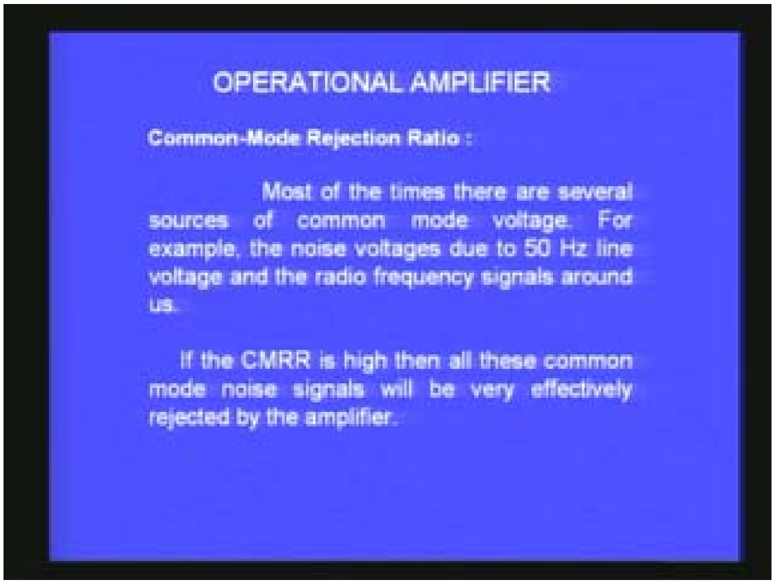

For example the 50 Hertz voltage, the radio frequency from the different television stations. All around us there are lot of electromagnetic waves present from different sources radio stations, television stations and communication lines, etc and all of them will be very, very small in magnitude. Even then the amplifier will not be able to distinguish them in principle it will also be amplified. All these noise voltages also will be amplified along with the signal which is the only thing that you want to concentrate on and the output will have enormous voltages coming from these noise voltages. Some times the noise voltages can completely swamp the signal that you wanted to observe. Then the signal will get buried in noise and you will not be able to see the signal very clearly. If I have a good CMRR, if I use a differential amplifier as the first stage and if that differential amplifier has got this characteristics which is called common mode rejection ratio CMRR very, very high then the amplifier will reject all the signals which are common to both the inputs very well, efficiently and all the signals which are common to the two input terminals or basically the noise voltages all around us and it will be very good noise rejection characteristics and what you get at the output will only be corresponding to the signal on which you are more interested. That is the reason why CMRR is the very very important characteristics of any differential amplifier and in particular operational amplifier.

I have given a typical example on the screen. If the op amp CMRR is about 100 db then it corresponds to 10 power 5. For every 20 db there will be a decade and so 100 db will have 5 decades and it will be 10 power 5.

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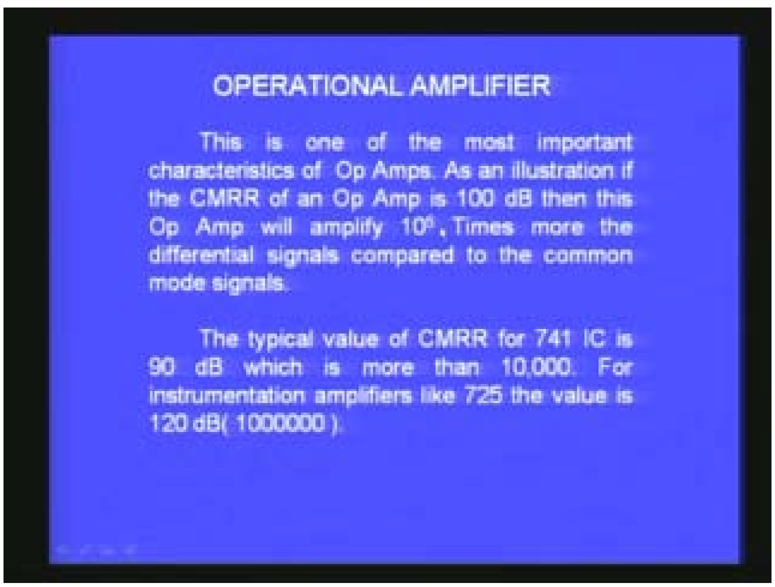

The differential voltages will be amplified nearly 10 power-? times more than the common mode signals that is what it says. The CMRR of 741 is 90 db which is about more than 10,000. There are some amplifiers which are called instrumentation amplifiers which are meant for applying to very low level signals. When you are trying to amplify very low level signals in the microvolts and the nano volts range the noise voltages also can be of the same magnitude and they can really harm the signal at the output. If I use a good instrumentation amplifier which is a high gain differential amplifier exclusively made with very large value of CMRR then the rejection of the noise will be very efficient. For example there is one op amp called 725 and the value of CMRR for 725 is 120 db because it is an instrumentation amplifier and that means the differential gain is about one million times more than the common mode signal. How do we get in principle the A_d and the A_c?

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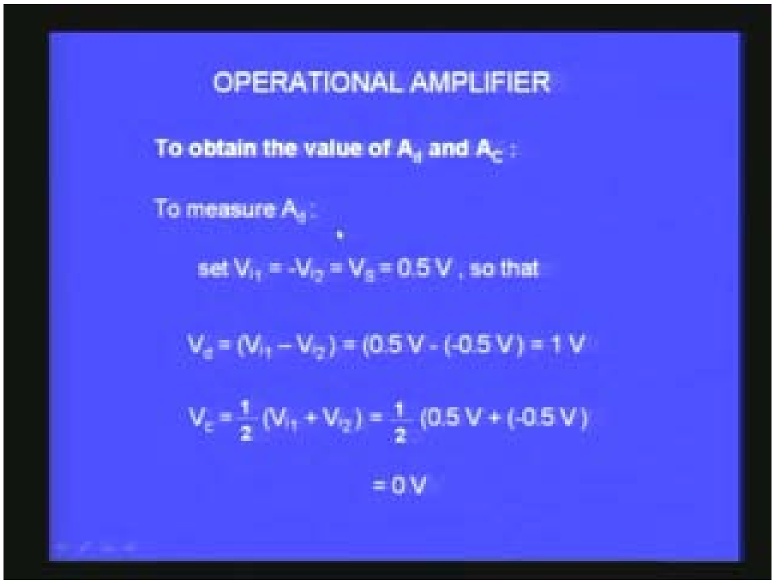

To measure Ad I can now set V_{i1} is equal to $-V_{i2}$ and that is equal to 0.5 volts. So I keep V_{i1} is equal to V_{i2} except for the opposite polarity. It is 0.5 volts plus and 0.5 volts minus and what will be V_d? V_d is V_{i1} minus V_{i2}; 0.5 volts – (- 0.5 volt). That is equal to 1 volt and what is V_c? V_c is half of V_{i1} plus V_{i2}; average of the two inputs. Half of 0.5 + -(0.5) and this becomes zero and therefore V_c is zero. What I have is V_d is equal to 1 volt V_c is equal to 0. V output V_0 now is equal to A_d V_d + A_c V_c.

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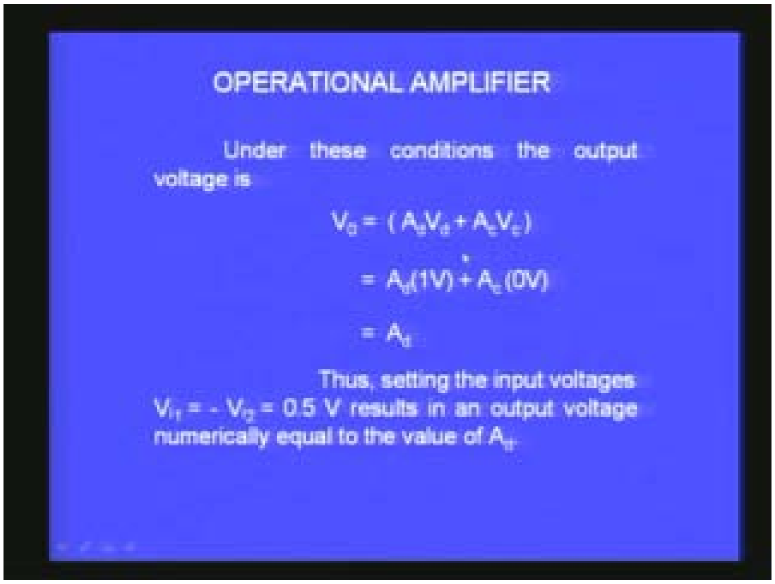

A_d into 1 volt + A_c into zero volts; anything into zero is zero and A_d into 1 volt is A_d. If now I measure what is the output voltage that in magnitude gives me the differential gain straight away. That is one way quickly to measure A_d. Similarly if I want to measure the A_c then I set V_{i1} is equal to V_{i2} is equal to 1 volt.

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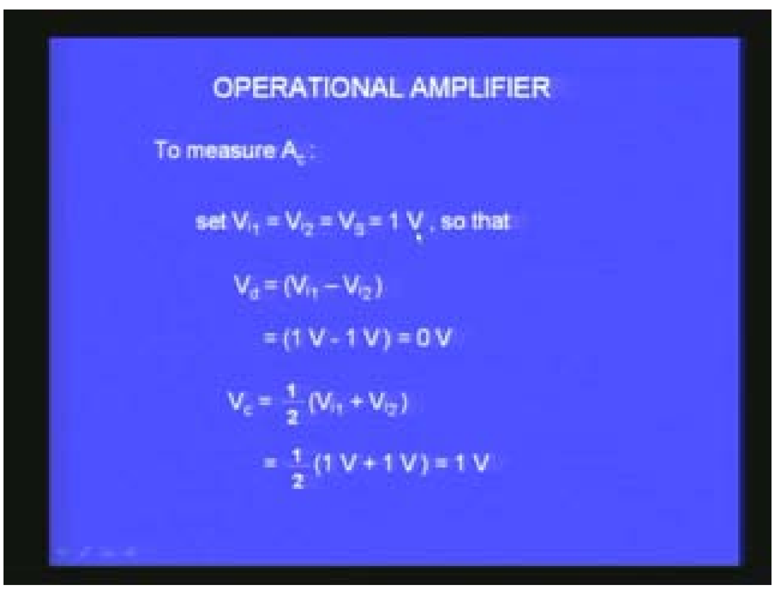

Then V_d is equal to V_{i1} - V_{i2}; 1 volt - 1 volt will give me zero. Therefore there is no V_d and V_c is average of half of V_{i1} + V_{i2}. That is equal to 1 volt and the output voltage is A_d into zero because now V_d is zero plus A_c into 1 volt. Therefore it is A_c.

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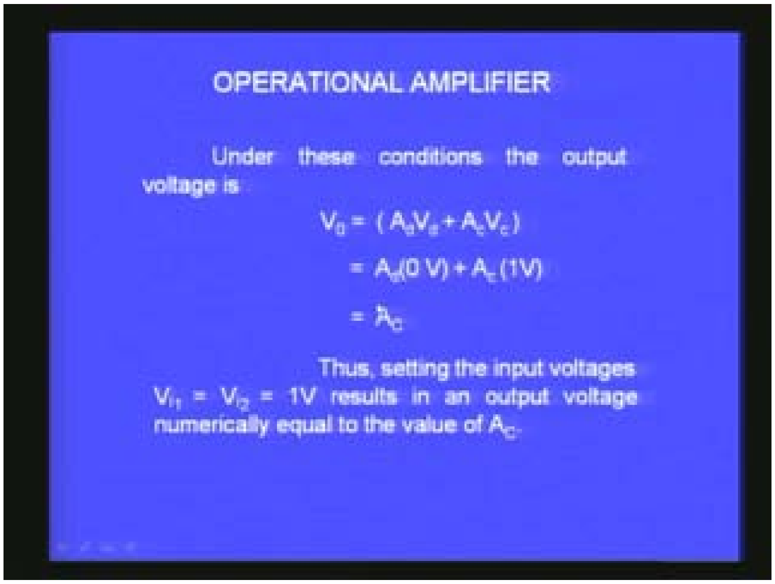

If I give 0.5 and -0.5 for the two inputs I get the output voltage in magnitude the A_d. If I give 1 volt and 1 volt at the input I get A_c as the voltage at the output. This is one simple way to measure A_c and A_d. Once you measure A_c and A_d you can get CMRR which is equal to A_d by A_c dividing the two. But unfortunately in practical situations it is a very difficult to set very precisely 0.5 volts and 0.5 volts because the 0.5 volts should be very precisely 0.5 volts up to 3 or 4 decimals because the gain could be very high and the output voltage can be very different even if there is a very slight difference between the two inputs. Only when I make both the inputs exactly equal using two sources I will be able to do this type of a measurement. In principle in practice it is going to be very difficult. We will use other techniques to measure the output voltage.

Now I want to try to impress up on you the concept of the CMRR in a much clear manner by giving another simple illustration. Let us assume that I have an amplifier with a gain 10. It is not a very large gain but it is only 10 and I have V_{i1} V_{i2}. I give 0 for V_{i1} and I give 100 millivolt for V_{i2}. What I expect 10 into the difference between these two is 100 millivolt. If it is a good differential amplifier it should only worry about the difference between the two inputs. If I have 0 and 100 millivolts for the two inputs the difference is 100 millivolts; that multiplied by 10, the gain is 1000 millivolt which is nothing but 1 volt.

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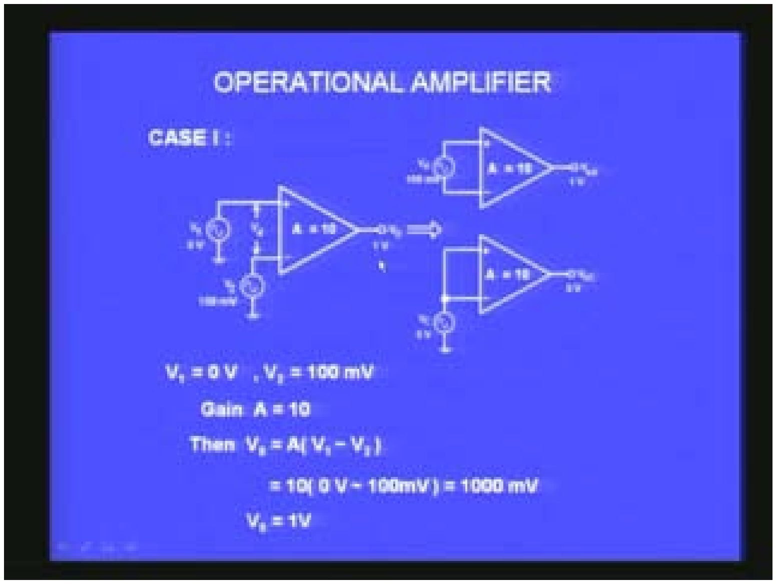

I must get only 1 volt at the output and the common mode signal is 0 here; here also it is 0 and the average value is around 50. That will be 50 into 10; 500 millivolt. That is what I will get. In a typical situation I give 0 volts here 100 millivolts I get 1 volt and then what I do is I modify. I give 1 volt at the input V_1 and 1.1 volt at the input V_2.

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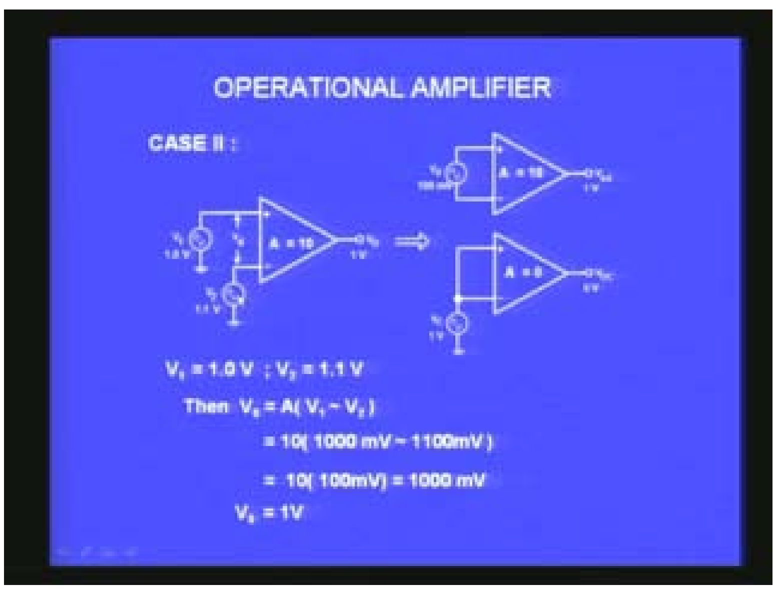

What do you mean by 1.1? It is 1 volt + 100 millivolt. This is 1 volt. One input is 1 volt the other input is 1 volt + 100 millivolt. The difference is still 100 millivolt. If the amplifier is a very good difference amplifier then it will now worry only about that 100 millivolt which is only the difference between the two inputs and that multiplied by 10 volt if I get 1 volt that means this type of amplifier is not at all worried about the signals which are common to both the inputs. Whether it is 0 and 100 millivolts or whether it is 1 volt and 1.1 or it is 5 volts and 5.1, the output voltage is 1 volt which is nothing but the difference in voltage multiplied by the gain 100 by 10 is 1 volt and that is constant irrespective of the common voltage that I have at the two inputs. If an amplifier can show such characteristics we call that amplifier an excellent amplifier, an ideal amplifier and the CMRR in this case can be infinity. It is completely able to reject all the common voltages.

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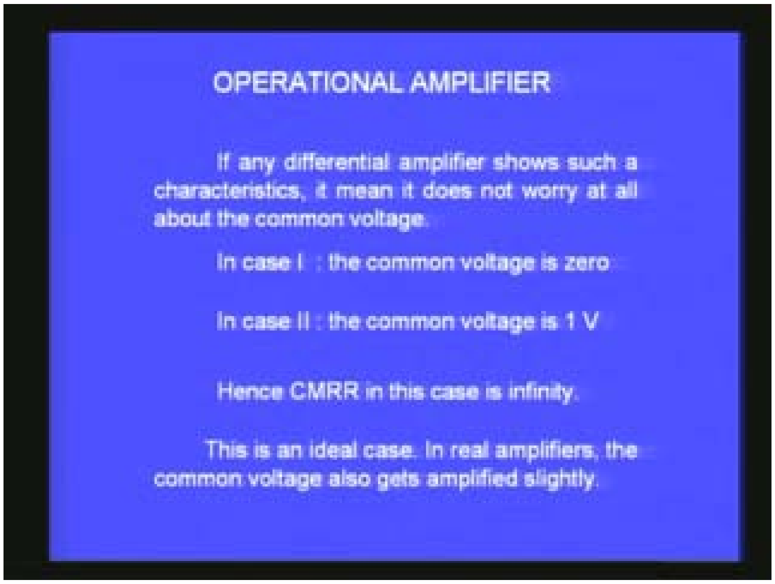

It is only amplifying the difference in the two signals. But I already mentioned to you in reality it is very difficult to get such high value CMRR. You can with great difficulty get a 90 db or 100 db etc. Let us now look at some small modification algebraic variation of the output voltage. Output voltage is equal to $A_d V_d + A_c V_c$.

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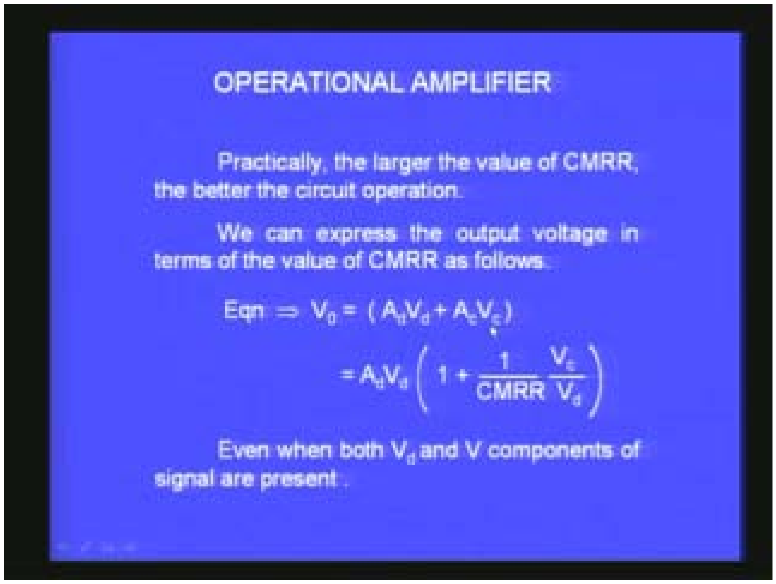

If I take this A_d V_d common outside it becomes 1 plus 1 by CMRR into V_c by V_d because A_d by A_c is CMRR. It is coming in the denominator. 1 by CMRR V_c by V_d. This formula is useful in doing some simple problems. I have also given an example here.

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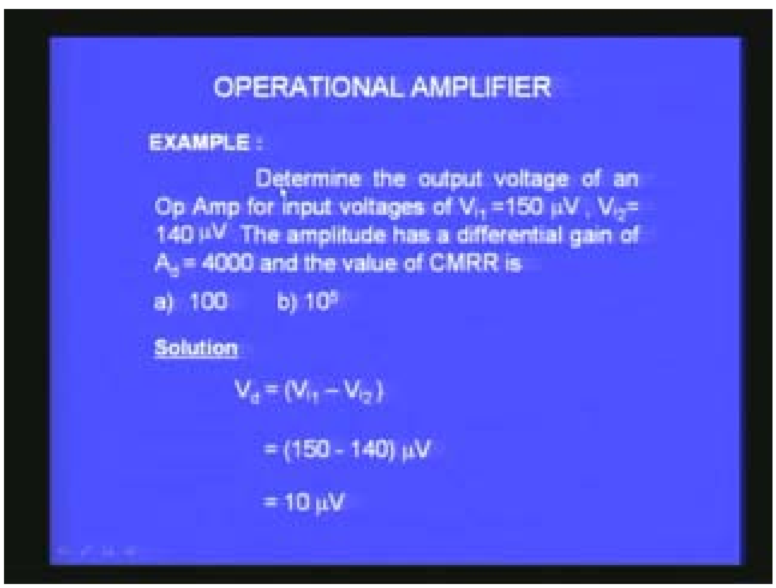

Determine the output voltage of an op amp for input voltages Vi1 is equal to 150 microvolt V_{i2} is equal to 140 microvolt. The amplitude has a differential gain of A_d 4000 and the value of CMRR is 100. Assume it is 100 and then b assume it is 10 power 5. What happens let us see? The two inputs are 150 and 140. So V_d is 150-140 microvolt and what I get is 10 microvolt and the common voltage is half of the two inputs. 150 +

140 by 2; that will be 145 microvolt and output voltages is A_d V_d into 1 plus 1 by CMRR V_c by V_d.

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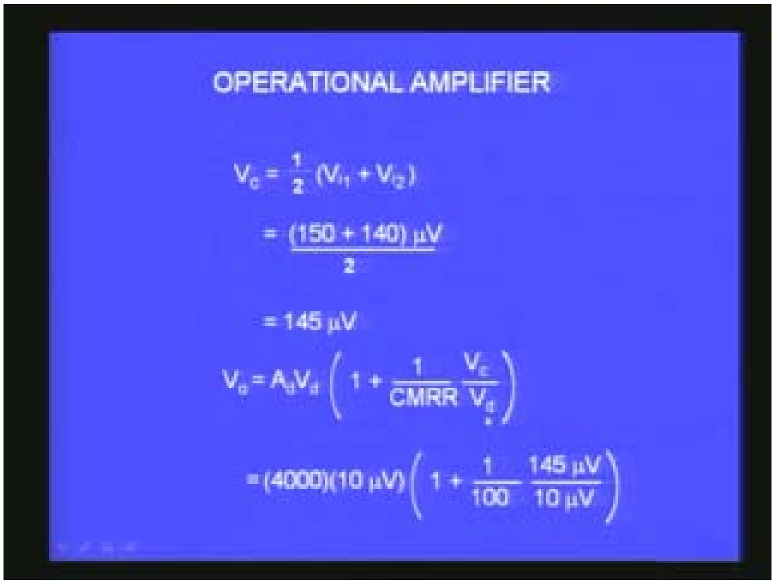

So 4000 multiplied by 10 microvolt which is the differential voltage 1 plus 1 by 100 for the first case the CMRR is 100 and 145 by 10 microvolt if you calculate it is 45.8 millivolts.

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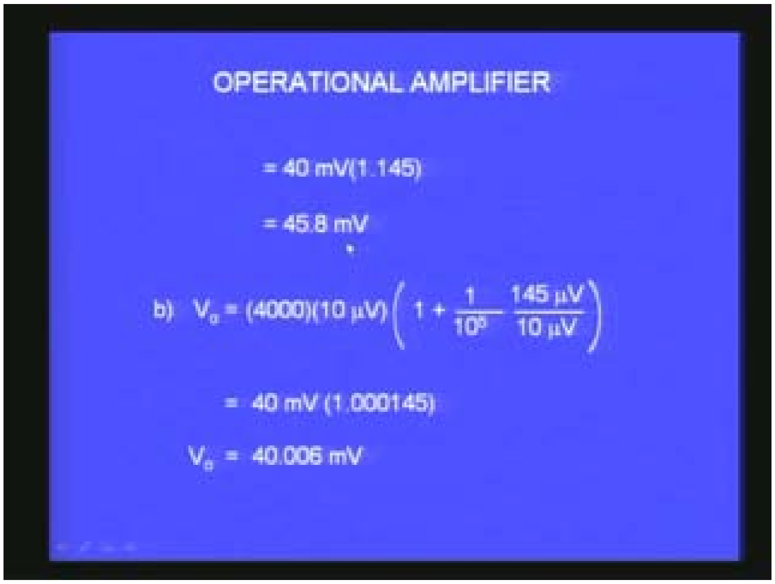

If you take the second case where it is 10 power 5, 4000 into 10 microvolt is the actual voltage you should get; 40 millivolts but you are getting 45.8 millivolt in one case because the CMRR there is smaller, only 100. When you have CMRR 10 power 5 this value becomes 40.006. That means if the CMRR is a very large value then the output voltage is almost equal to the 4000 multiplied by 10 microvolt. That means A_d into V_d the contribution from the second term will almost be very, very small. That is what we try to understand from this example. When the CMRR is high it becomes a very good differential amplifier which is always concerned only between the difference in the two inputs and it not so much worried about the common signals.

How do we actually measure CMRR in the laboratory? That is our next problem. For that we have to measure A_d and we have to measure A_c.

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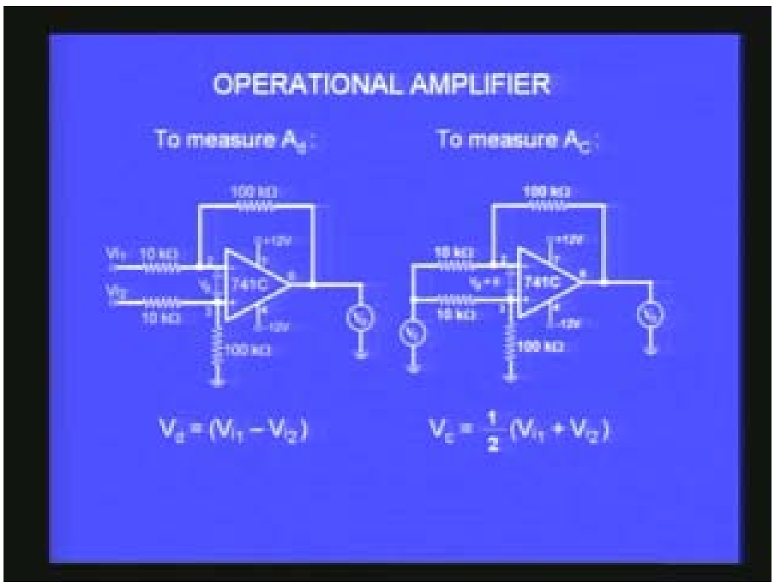

Let us see how we can practically do this in the laboratory by measuring the A_d and A_c. I have given you two circuits on the screen. This is a differential amplifier. I have used 10K and 100K in the feedback and again 10K and 100K. This is a differential amplifier configuration. We have not discussed this yet but we will discuss it shortly in one of the lectures later. But for the present you can assume this to be a differential amplifier and the V_d here is V_{i1} minus V_{i2} and I will measure what is the output voltage? I will give one voltage here I will give another voltage to the other input. I will find out what is the difference and I will measure the output. Output divided by the difference in the two inputs will give me the gain corresponding to the differential amplifier A_d. It is a very simple measurement. Then if you want to measure common mode gain then what you do is you connect the two input terminals together and connect a voltage source together. This is the common mode configuration which we already discussed. Now measure the output for the same amplifier and divide the output by the common mode input signal and that will give the A_c, the common mode gain. This is a simple practical way of measuring the A_d and the A_c. Once you measure A_d and A_c you can divide one by the other and you can obtain the common mode rejection ratio.

Now I will take a typical numerical example here which is similar to what I would be doing later on in an actual demonstration.

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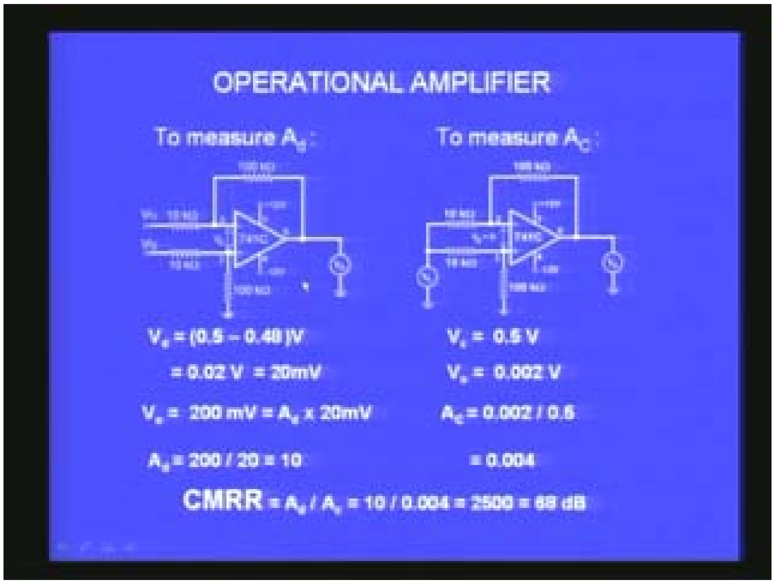

What I have done is I have applied V_{i1} to be 0.5 volts and V_{i2} is slightly different that is 0.48 volts. What is the differential voltage? 0.5 – 0.48 and that is 0.02 volts or in principle it is 20 millivolts. The differential voltage at the input terminal of a differential amplifier is 20 millivolts and the gain is 10 here 100K and 10K. The output voltage if I multiply by 10 it will be 200 millivolts. A_d into 20 millivolts is 200 millivolts. I can find out the A_d; A_d is 200 by 20 is 10. By measuring the output voltage which is 200 millivolt and measuring the input difference which is 20 millivolt, 200 by 20 is 10 and I know A_d. We know from the value of resistors that I have used it is also 10 in this case. But in principle even if you don't know by measuring the output voltage and the difference in the input voltage I can directly divide and obtain the value of the differential gain.

In the second case I have connected the two input terminals and applied 0.5 volts constant. Now what is the output voltage I measure? I measure 0.002 volts or close to that. What is the gain? Voltage output divided by the voltage input; 0.002 divided by 0.5 and it is 0.004 volts. The gain is 0.004. I have now got the A_d which is 10 and A_c which is 0.004. That means it is very, very small value. The common mode gain is a small value. It is not amplifier at all. It is actually attenuator it has reduced the output voltage. CMRR is A_d by A_c and that is 10 by 0.004 and that is around 2500 or so and if I convert it into db by multiplying 20 log 2500 to the base 10 it's around 68 db. The actual typical value for 741 is around 90 db. It's about 70 db what we measure here typically. It is possible in a laboratory to actually perform this experiment and measure the CMRR for the operational amplifier which is what I am going to do now.

I am going to show you a demonstration. Here you can see I have got the two circuits which I just discussed. This is in the differential mode so that there is a separate V_{i1} and a separate V_{i2} in the circuit and here is the common mode signal. I have connected the two input terminals together and applying the voltage here. I am going to do these two and measure the output in each case and measure the output by the difference in voltage in this case that will be the A_d; measure the output and corresponding input here that will be the A_c. Then I will divide one by the other to obtain the CMRR.

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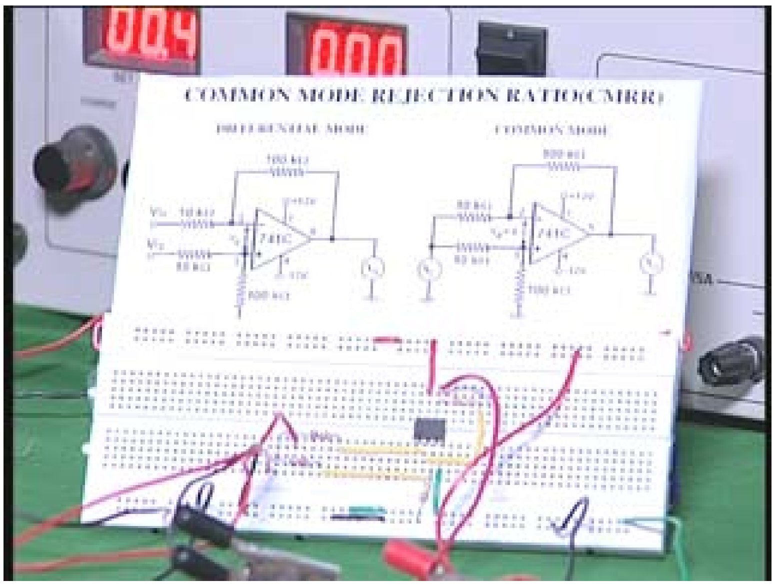

I have used one of the voltage source V_{i1} 0.5 here. This is actually 500 millivolt corresponding to 0.5 volts that is connected to one of the input terminals and I have used one of the power supplies which is not being used here, a variable power supply. That output voltage it is actually 0.49 and that is what is given here. I can first use the multimeter which is here. I will connect the multimeter to the two inputs and measure the voltage here. Concentrate on the voltmeter while I connect to the two inputs. I take the multimeter and connect to the input terminal one. It is 0.5 volts. That is V_1.

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I take it out and connect to the second input and it is 0.479 or 0.48.

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The difference is 0.5 - 0.48. It is 20 millivolts and now I take it out and connect it at the output terminal. The value at the voltmeter is 200. 20 millivolts is the difference multiplied by the 10 which is the gain of the amplifier is 200. That is what we got at the output.

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This differential gain is 20. I am going to remove these two input voltages and connect the two input terminals together and connect one of the 0.5 volts alone. There is a red wire which has come in the circuit which is actually connecting the two input terminals V_1 and V_2 and there is only one source, this source which is connected at the input and this is already 0.5. I have not changed anything here.

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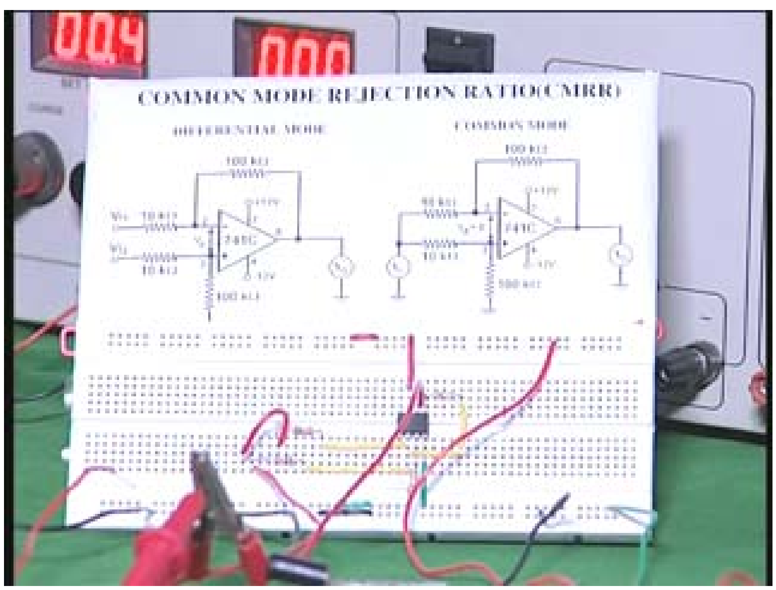

0.5 volts is given at the input and what is the output voltage? The output voltage is 0.456.

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This is 0.456. The gain is nearly less than 1. This is 0.5 and this is 0.456. The output voltage is nearly 0.008 or 0.009.

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It is a very, very low value and 0.5 divided by 0.009 is the A_c and it is going to be very, very small and then we already saw the differential gain is 10. This voltage 0.009 divided by 0.5 is about 0.002 and you will get around 5000 as the CMRR. 5000 will be the CMRR and if you look at the db this will be nearly 80 db; close to 80 db, 75 db or so. We saw how we can measure in the laboratory the CMRR and now we will move on to the next characteristic which is the basically the transfer characteristics of an operational amplifier. This is also a very important characteristics and what we mean by that here is if I have an input and an output what will be the graph between the input and the output.

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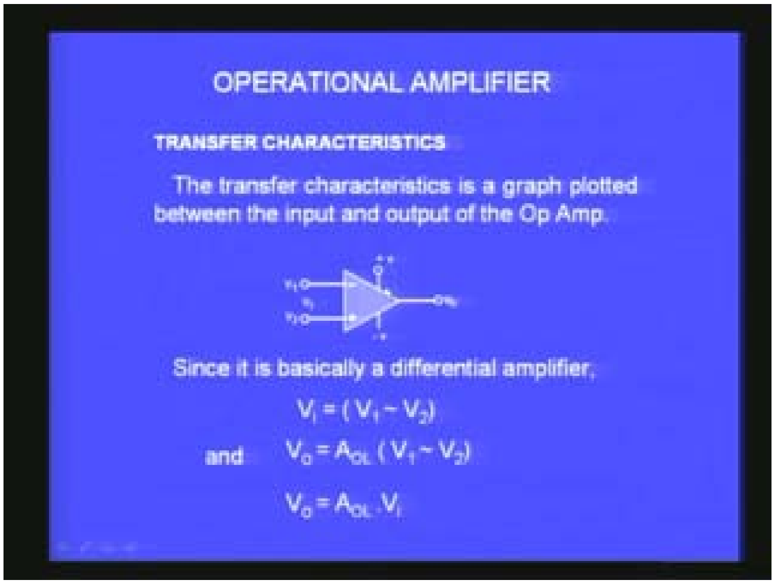

The transfer characteristic is a graph plotted between the input and output of the op amp. Since basically it's a difference amplifier V_i is equal to V_1-V_2 the difference of the two and V output is A_{OL} the open loop gain multiplied by the difference. But A_{OL} the open loop gain of an operational amplifier is typically 10 power 5; 100,000.

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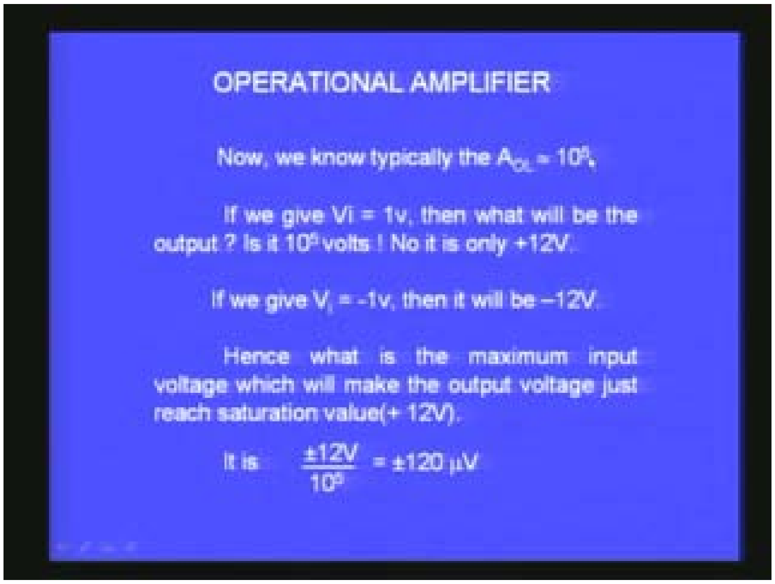

If we give V_i to be 1 volt then what will be the output without any feedback. A_{OL} means what? Open loop gain; open loop gain means there is no feedback. If I have that the output should be 10 to the power of 5 volts. Can I get 10 power 5 volts at the output by giving 1 volt? You can never get because the output voltage can never be greater than the power supply voltage and the power supply voltage is only + 12 volts or -12 volts because it is a dual supply and the output voltage whenever it exceeds by a simple formula V_o is equal to A_{OL} by V_i. When it exceeds 12 volt it will saturate at 12 volts. For all higher values of voltages at the input, the output voltage will remain constant at +12 volts and it will not increase beyond there; similarly for the negative side. There is a limit to the output voltage corresponding to + or - 12 volts or + or - V_{cc} as we call it. That shows what will be the limit of the input voltage? The limit at the input voltage should be + or -12 volt which is the limit for the output voltage divided by the gain gives me the input voltage. + or -12 volt by 10 power 5 gives me + or -120 microvolts. I multiplied numerator and denominator by 10; so it is about 120 microvolts. That means what? An operational amplifier will obey the equation V output is equal to A_{OL} into V_i only when the input ranges are between the two input terminals; the voltages are + or -120 microvolts or less. Whenever it exceeds 120 microvolts or more the output voltage will saturate either at the + or - depending upon which polarity of the voltage is higher. This is what we call the transfer characteristics of the operational amplifier. I have shown a graph here.

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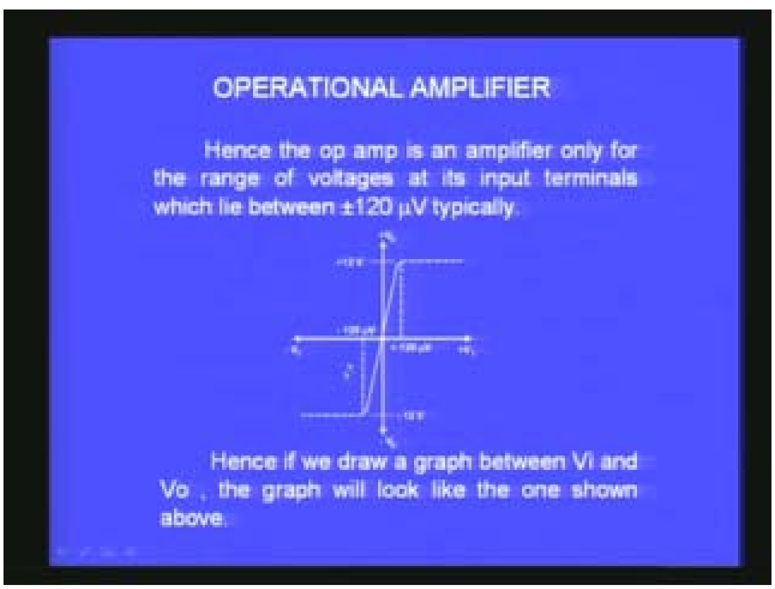

This is the V input and this is the V output the vertical line and till 120 microvolt there is a linear relationship passing through the origin which corresponds to the amplifier behavior and beyond that 120 microvolt the output voltage remains constant at +12 volts on the positive side and on the negative side it remains constant at -12 volts. We are using operational amplifier in all the applications that we are going to discuss as an amplifier confined to this small range where the difference between the two input terminals at the op amp is + or - 120 microvolts. This graph that you get is what is known as the transfer characteristics and it is a very, very important characteristics. If you look at the slope of this line, the slope of the line will be the gain, open loop gain of the operational amplifier 10 power 5 in this case. If you look at the point going through zero if it is perfectly going through zero that means it has got no offset voltage. When the input voltage is zero the output voltage is also zero

But in principle we already saw for a typical real operational amplifier this is not the case. You will have a small offset voltage and this will not exactly pass through the center. Only in an ideal case it will pass through the center. This + or -120 microvolts limit is very, very important to remember. Because this is a very small value in all practical operational amplifier if it is working as an amplifier if you measure the voltage between the two input terminals it should be almost the same. For example if I measure at one input terminal 1 volt the other input terminal if it is an amplifier configuration cannot be other than 1 volt + or - 120 microvolts and both the terminal voltages should be same if the operational amplifier is performing as an amplifier and this is very important especially when you are doing trouble shooting. When an operational amplifier is not working; it is configured as an amplifier and it is not working. You want to know the problem with the circuit. All that you have to do is see whether all the voltages are coming properly at the V_{cc}, $+V_{cc}$ and $-V_{cc}$ at the pins of the operational amplifier and then you should find out whether at the two input terminals the voltages at V_1 and V_2 are very close to each other; almost same + or -120 microvolt and if that happens that means the operational amplifier is in good condition. If you find the two voltages are different by more than 1 volt or 0.5 volt then you immediately can conclude there is something wrong with either the operational amplifier or any of the connections around it. You can analyze them in much more detail and find out what is wrong in the circuit.

In the next lecture I will briefly touch upon this transfer characteristic and then I will also show you a demonstration of how to measure the transfer characteristics. I already mentioned to you the transfer characteristics will be very, very useful in several applications like the comparator. There are lots of applications related to the comparator. I will also show you the transfer characteristics using an oscilloscope and then we will discuss the other parameters and the characteristics of the operational amplifier. Thank you!