Basic Electronics
Learning by doing
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Lecture – 31
(Instrumentation, transducers, current booster (uni - bi), VCIS, howland...)

Hello everybody! In our series of lectures on Basic Electronics learning by doing let us move on to the next. Before we do as usual it will be nice to recapitulate what we discussed in the previous lecture.

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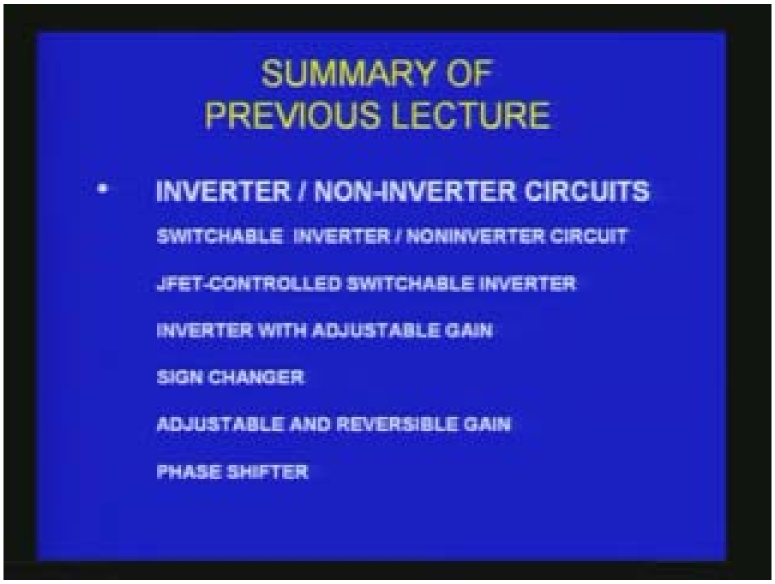

SUMMARY OF
PREVIOUS LECTURE

- INVERTER / NON-INVERTER CIRCUITS
  SWITCHABLE INVERTER / NONINVERTER CIRCUIT
  JFET-CONTROLLED SWITCHABLE INVERTER
  INVERTER WITH ADJUSTABLE GAIN
  SIGN CHANGER
  ADJUSTABLE AND REVERSIBLE GAIN
  PHASE SHIFTER

You might recall that we discussed about the inverter/non-inverter circuits, the switchable inverter circuits, the non-inverter circuits and then JFET, the junction field effect transistor controlled switchable inverting circuit amplifier and then inverting amplifier with adjustable gain and we also saw the sign changer. How you can either make it plus or minus that is 180 degrees out of phase or the other way and then we also looked at adjustable and reversible gain. We can go from for example a gain which is -100 up to +100 by moving the potentiometer. We also saw at the end how the phase shifter can be built using operational amplifier. All these circuits we saw under what I would call as application circuits of operational amplifiers

Let us move on to further application circuits of operational amplifier and one which we will be discussing today is what is called instrumentation amplifier. In many instrumentation applications you will have very low signals from may be some sensors or transducers and you would like to amplify them and then read them for either control or measurement. In such situations operational amplifiers are very, very useful. There are some specific configurations which are called instrumentation amplifier configurations which we will discuss and they have certain specific advantages over the normal operational amplifier that we make use of. There are instrumentation amplifiers that you can also commercially buy from the market and some of them are very, very good but they are also very expensive. What I am going to do today is explain to you how a simple instrumentation amplifier configuration can be built by using standard operational amplifier. The one we normally discuss is a 741 operational amplifier which is very popular.

Instrumentation amplifiers are used in several applications from simple motor control to data acquisition and automotive circuits and we will study only the fundamentals; basic functional configurations of the instrumentation amplifier.

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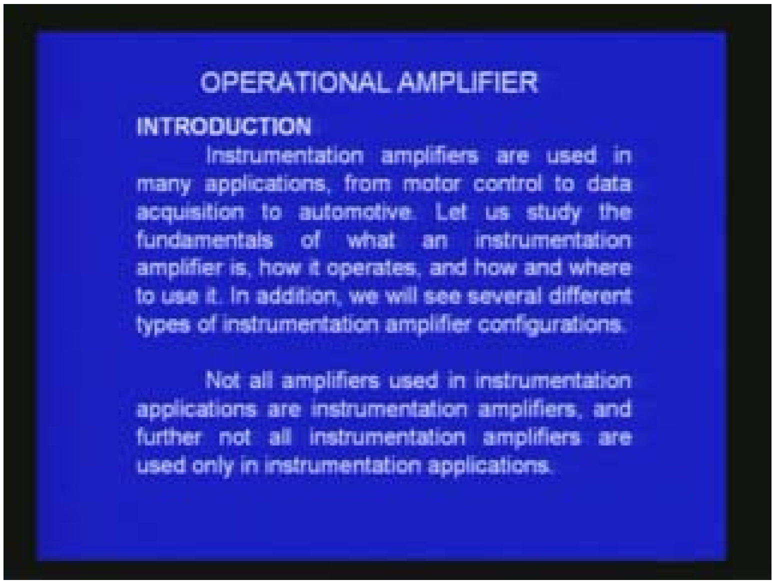

OPERATIONAL AMPLIFIER

INTRODUCTION

Instrumentation amplifiers are used in many applications, from motor control to data acquisition to automotive. Let us study the fundamentals of what an instrumentation amplifier is, how it operates, and how and where to use it. In addition, we will see several different types of instrumentation amplifier configurations.

Not all amplifiers used in instrumentation applications are instrumentation amplifiers, and further not all instrumentation amplifiers are used only in instrumentation applications.

We will see two, three configurations; how each one is an improvement over the previous one. It is to be mentioned that not all amplifiers used in instrumentation applications are instrumentation amplifiers. There could be other types also and in the same ……. all instrumentation amplifiers are not all the time used only in instrumentation amplification applications. You can think of other applications for instrumentation amplifiers. The basic idea behind the instrumentation amplifier is that it should have very high gain and it should have very good CMRR.

I explained to you what CMRR is. CMRR is common mode rejection ratio which we know is the figure of merit to tell us about how good is the amplifier in rejecting signals which are common to the two inputs and preferentially amplifying only the difference signals. This is a very important characteristic of every differential amplifier and operational amplifiers being a differential amplifier they have to have good CMRR. If we have a very high CMRR then that is one of the criteria for a good instrumentation amplifier. The normal typical value of the CMRR for 741 is from 70 to about 90 db; decibel units. You all know what the decibel unit is. We have already explained and if you look for very specific instrumentation amplifiers they will have very high CMRR.

For example 110, 120 is a very common instrumentation amplifier. 725 is one good instrumentation amplifier which has got CMRR around 120 db which if you calculate in terms of 20 db per decade it will be 10 power 6. That means it will amplify differential signals 10 power 6 times compared to the common mode signals because the CMRR actually gives you the ratio of the differential gain to the common mode gain. It will preferentially amplify difference signals by nearly 1 million times. That's a very wonderful number and they are very, very useful in several low signals and on a noisy environment. Because noise signals will be common to both the inputs that way the noise signals become the common mode signal and this CMRR tells you how good is the amplifier in rejecting all those which are common and in that sense the noise performance of the amplifier will be excellent when you have very high CMRR. But CMRR also will depend on the frequency and several other parameters and so one has to take note of this point that the CMRR that we normally talk about are for low frequency applications.

You can see on the screen one of the simplest configurations of an instrumentation amplifier and that as I already mentioned to you is a very simple differential amplifier which we have already discussed and seen.

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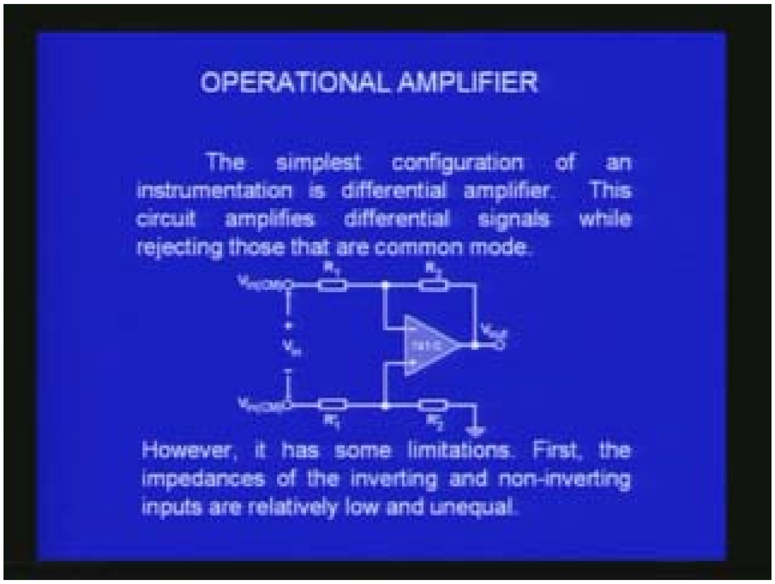

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The simplest configuration of an instrumentation is differential amplifier. This circuit amplifies differential signals while rejecting those that are common mode.

However, it has some limitations. First, the impedances of the inverting and non-inverting inputs are relatively low and unequal.

In this amplifier you have V_{in}, V_{in1} and V_{in2}. They are actually the common mode signals which are applied and if it has got a good CMRR these are all going to be rejected and what is going to be amplified is only the difference in the signal between these two points and that will be amplified by the differential amplifier. We have also derived the expression in an earlier lecture the gain of the amplifier is $-R_2$ by R_1. Deliberately if I keep R_2 prime and R_2 equal and R_1 and R_1 prime equal then you can have the ratio R_2 by

R_1 about100. This can be 100K. This could be 1K; R_1 can be 1K, R_2 can be 100K. Then R_2 by R_1 will be 100K by 1K which is about 100 times and the gain will be 100 multiplied by the difference in voltage between the two inputs. This is a very simple configuration of an instrumentation amplifier.

That is precisely what I am saying here but what I have considered here is if R_1 is equal to R_1 prime is equal to R_2 prime and R_2 and if I make all of them 100K for example, in a typical situation then the differential gain is only 1. In this case because all the resistors are 100K it will be -1.

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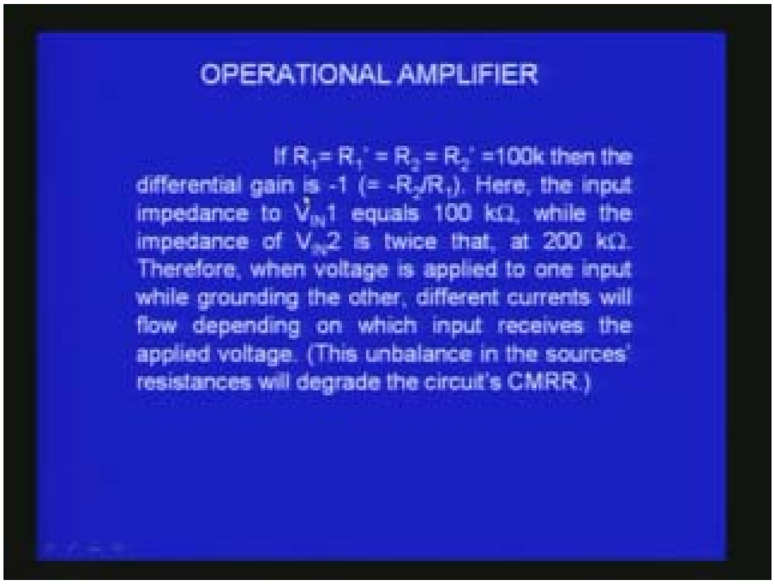

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If $R_1 = R_1' = R_2 = R_2'$ =100k then the differential gain is -1 (= $-R_2/R_1$). Here, the input impedance to $V_{IN}1$ equals 100 kΩ, while the impedance of $V_{IN}2$ is twice that, at 200 kΩ. Therefore, when voltage is applied to one input while grounding the other, different currents will flow depending on which input receives the applied voltage. (This unbalance in the sources' resistances will degrade the circuit's CMRR.)

Hence the input impedance of the V_{in} input will be 100K while that of the second one will be 200K; twice and therefore the two impedances are not equal. This is one of the very important considerations in the instrumentation amplifier. When a simple differential amplifier is considered the impedances at the two inputs are not equal. Because of that even the common mode signals will generate different currents through the input impedances and because of the differences in the impedances even the common mode signal will introduce a differential voltage and that also get amplified along with the other differential signals and the CMRR will be brought down because of this. One should take note of it that the two inputs because they don't have same impedance there will be degradation in the performance of the amplifier. It will bring down the CMRR.

Apart from that there is another source for bringing down the CMRR in a simple differential amplifier that we are discussing and that is basically to do with the tolerances of the resistors that we use in the circuit.

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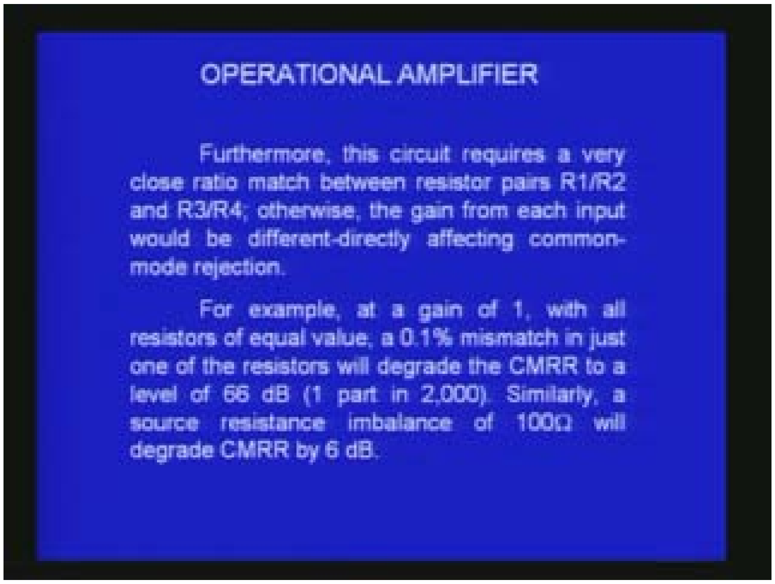

OPERATIONAL AMPLIFIER

Furthermore, this circuit requires a very close ratio match between resistor pairs R1/R2 and R3/R4; otherwise, the gain from each input would be different-directly affecting common-mode rejection.

For example, at a gain of 1, with all resistors of equal value, a 0.1% mismatch in just one of the resistors will degrade the CMRR to a level of 66 dB (1 part in 2,000). Similarly, a source resistance imbalance of 100Ω will degrade CMRR by 6 dB.

All resistors that we make use of in the lab have specific tolerance. What do I mean by tolerance? There will be a silver line or a gold line at the end. In the color code you would have studied that the first three color codes are corresponding to the numbers and the exponents and the last one, the fourth one normally is meant to indicate the tolerance of the resistor. That means for example if it is silver it is 10%. That means what? If I take 100K the value of that resistor can be 10% plus or minus with reference to 100K. If the tolerance is going to be different what you say as 100K in the circuit may not be 100k. It can be 90K or it can be 110K or it can be any value in between and these differences in the resistances due to the tolerance can also lead to slight differences in voltages at the input and the output and that will also bring down CMRR. Because these differences will start giving a differential signal for the common mode signal applied to the two inputs and that will lead to an additional differential signal. I have given an example on the screen. At a gain of 1, simple unity gain with all resistors of equal value a 0.1% mismatch in just one of the resistors will degrade the CMRR to a level of 66 db; 1 in 2000. Similarly a source resistance imbalance of about 100 ohms will degrade CMRR by 6 db. The effect of these tolerances of the resistors that we use in the circuit can also lead to a degradation of the CMRR. This we have to take note of. In such applications you must able to get very precise value of resistors preferably 0.1% or even better.

When you have the common mode input voltage only you must have zero output because the CMRR will make sure that the common mode signals are not amplified.

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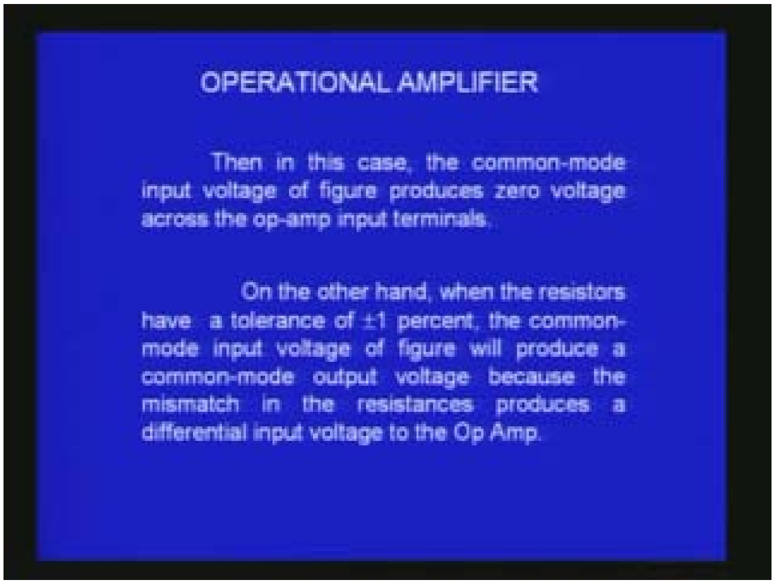

OPERATIONAL AMPLIFIER

Then in this case, the common-mode input voltage of figure produces zero voltage across the op-amp input terminals.

On the other hand, when the resistors have a tolerance of ±1 percent, the common-mode input voltage of figure will produce a common-mode output voltage because the mismatch in the resistances produces a differential input voltage to the Op Amp.

But because the resistors have tolerances plus or minus 1% you would get a corresponding differential voltage produced by the common mode voltages and that also will get amplified by the large differential gain of the differential amplifier and that will also add to the already existing differential signal. Your signal will no more be pure due to the difference in signal that you apply at the input but it is also due to some slight differences in the resistances. This we should avoid. I have tried to explain it in some more detail.

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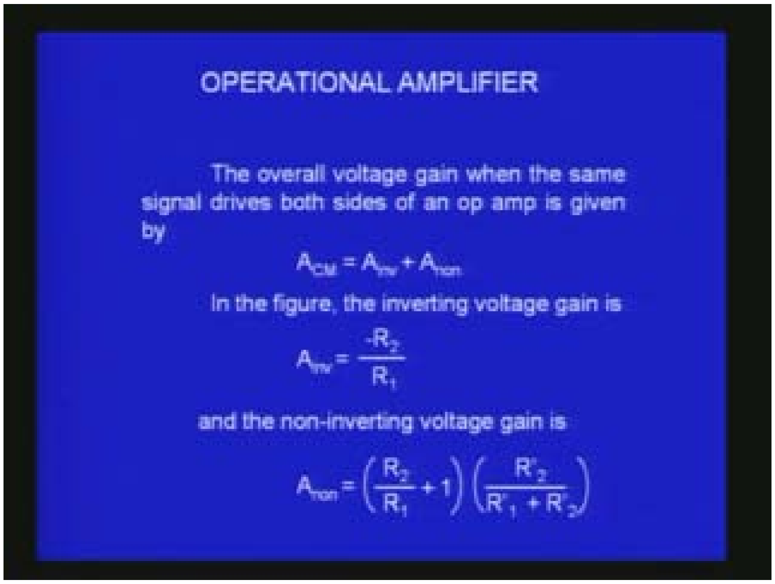

OPERATIONAL AMPLIFIER

The overall voltage gain when the same signal drives both sides of an op amp is given by

$$A_{CM} = A_{inv} + A_{non}$$

In the figure, the inverting voltage gain is

$$A_{inv} = \frac{-R_2}{R_1}$$

and the non-inverting voltage gain is

$$A_{non} = \left(\frac{R_2}{R_1} + 1\right)\left(\frac{R'_2}{R'_1 + R'_2}\right)$$

The overall voltage gain when the same signal drives both the inputs, inverting input and the non-inverting input of the operational amplifier is given by A_{CM}. It is completely the common mode. The common mode gain which is shown by A suffix CM, common mode amplification is equal to the gain corresponding to the inverting input plus the gain corresponding to the non-inverting input. In the previous figure differential amplifier that I showed the inverting voltage gain is very simple. A inverting is equal to $-R_2$ by R_1; simple inverting amplifier gain and the non-inverting voltage gain is 1 plus R_2 by R_1 if I apply at the positive terminal. I will go back to the circuit and show you. If I now ground this input, the inverting input and give the voltage directly at this node then the amplifier gain is 1 plus R_2 by R_1 times whatever input that you give here.

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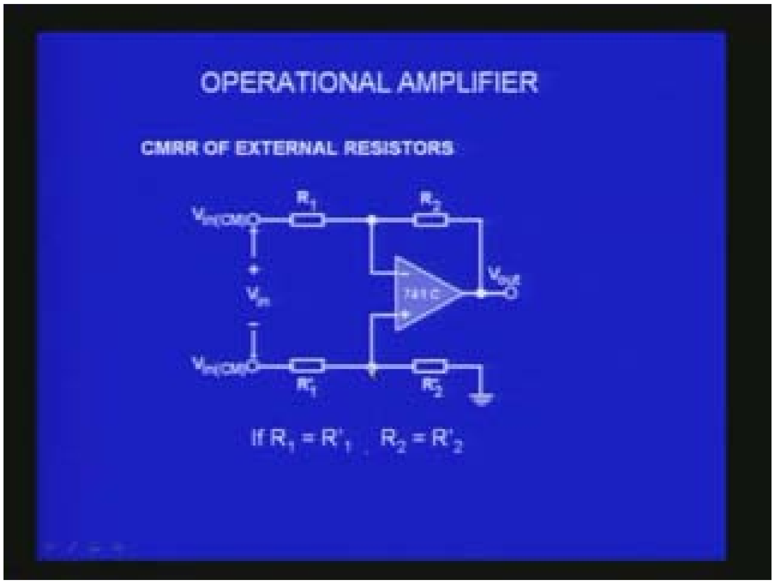

OPERATIONAL AMPLIFIER

CMRR OF EXTERNAL RESISTORS

If $R_1 = R'_1$, $R_2 = R'_2$

But in the present configuration you are giving the input at this point and that is going to be divided by a potential divider formed by R_1 prime and R_2 prime. The voltage here is going to be R_2 divided by R_1 plus R_2 times this common mode signal at the non-inverting input. This will now be multiplied by 1 plus R_2 by R_1 to get the over all gain of the non-inverting amplifier. That is what I have written here. A non-inverting is equal to 1 plus R_2 by R_1 which is the basic gain of the non-inverting input multiplied by the ratio R_2 prime divided by R_1 prime plus R_2 prime which is coming because of the potential divider formed by R_1 prime and R_2 prime. This is the gain corresponding to the non-inverting voltage. I now add the two because I want to find out the total overall common mode gain. A_{CM} is equal to A inverting plus A non-inverting. and that is when you take that non inverting we have already got that and we have we have to multiply by the corresponding R two by corresponding inverting amplifier.

We can derive this useful formula for example A_{CM} is equal to plus or minus 2 delta R by R where delta R by R is what is know as the tolerance. The change in the resistance with reference to the actual magnitude for R_1 is equal to R_2. To make that we have made all the resistors equal. R_1 is equal to R_2. Then the common mode gain will be plus or minus 2 into delta R by R by bringing in the variation in the resistor. The common mode gain will be plus or minus 4 delta R by R when R_1 varies very, very small compared to R_2.

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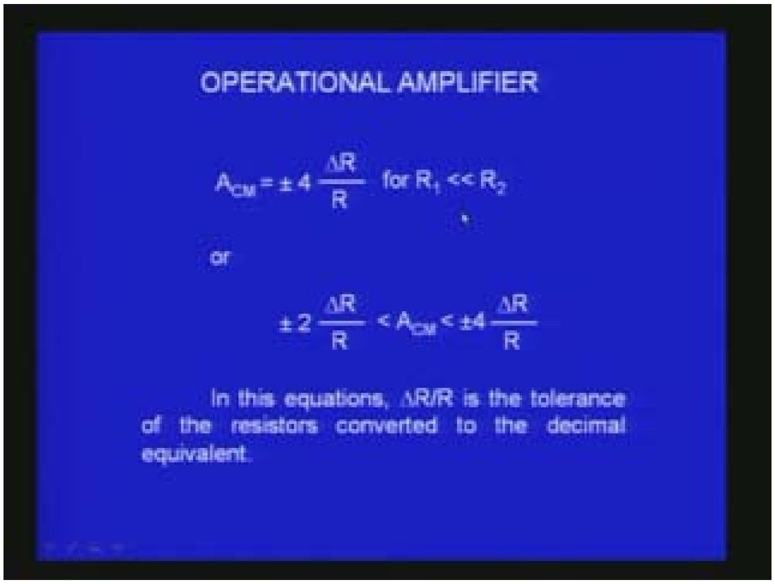

OPERATIONAL AMPLIFIER

$$A_{CM} = \pm 4 \frac{\Delta R}{R} \quad \text{for } R_1 << R_2$$

or

$$\pm 2 \frac{\Delta R}{R} < A_{CM} < \pm 4 \frac{\Delta R}{R}$$

In this equations, $\Delta R/R$ is the tolerance of the resistors converted to the decimal equivalent.

This will be the gain or what we can say is the maximum value to the minimum value. We can say plus or minus 2 into delta R by R and plus or minus 4 into delta R by R. The two extreme values within which the common mode gain can change where the delta R by R is the tolerance of the resistors converted into the decimal equivalent. The common mode gain can become a function of the tolerances of the resistors and if the tolerance of resistor is taken care of if it is 0.1% then the overall performance will be better because the common mode gain will be much smaller. I have taken an example here in the circuit.

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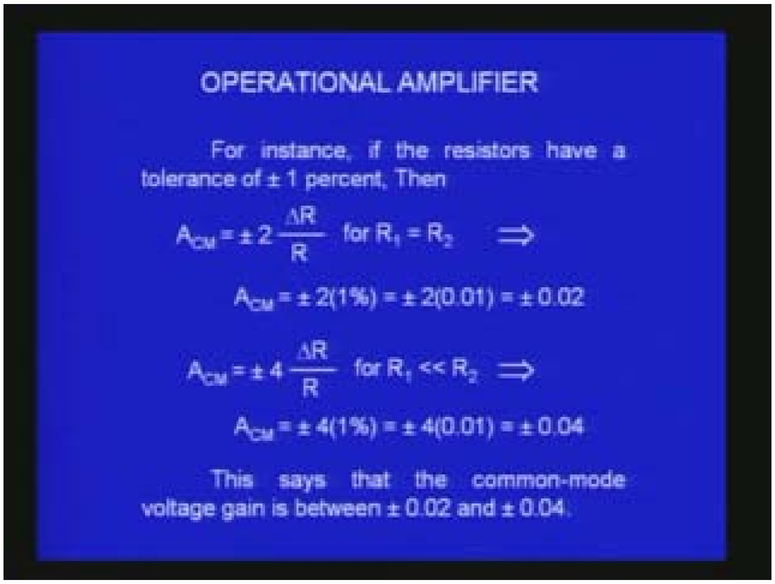

OPERATIONAL AMPLIFIER

For instance, if the resistors have a tolerance of ± 1 percent, Then

$$A_{CM} = \pm 2 \frac{\Delta R}{R} \quad \text{for } R_1 = R_2 \quad \Rightarrow$$

$$A_{CM} = \pm 2(1\%) = \pm 2(0.01) = \pm 0.02$$

$$A_{CM} = \pm 4 \frac{\Delta R}{R} \quad \text{for } R_1 << R_2 \quad \Rightarrow$$

$$A_{CM} = \pm 4(1\%) = \pm 4(0.01) = \pm 0.04$$

This says that the common-mode voltage gain is between ± 0.02 and ± 0.04.

For example if I have plus or minus 1% tolerance what will be the variation? The common mode gain will be plus or minus 2 into delta by R. For R_1 is equal to R_2 that will be plus or minus 2 into 1% and 1% is 0.01. That means plus or minus 0.02 and if R_1 is very, very small compared to R_2 it will be 4 times delta R by R and that will give me 0.04 plus or minus as the common mode gain. The common mode voltage gain will lie between these two limits; either plus or minus 0.02 and plus or minus 0.04 and when R_1 is equal to R_2 the differential voltage gain becomes -1 and plus or minus 2 into 0.1% is 2 into 0.001 and that is equal to plus or minus 0.002.

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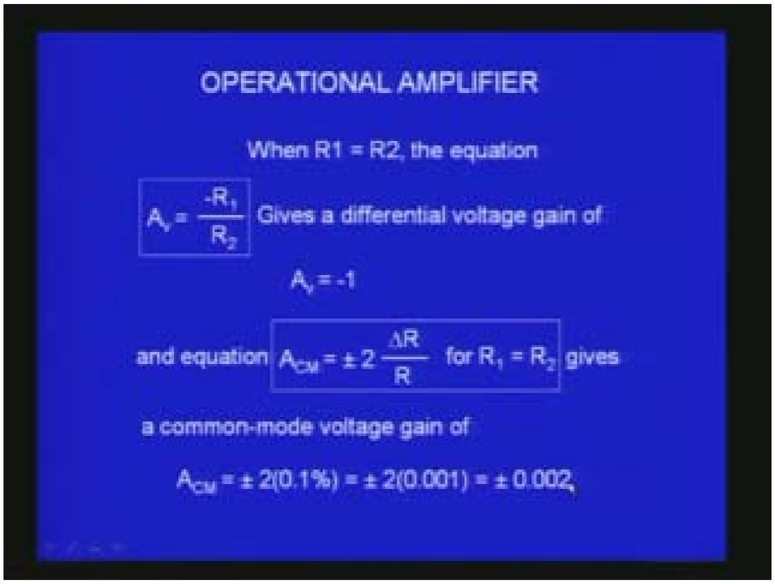

OPERATIONAL AMPLIFIER

When R1 = R2, the equation

$\boxed{A_v = \frac{-R_1}{R_2}}$ Gives a differential voltage gain of

$A_v = -1$

and equation $\boxed{A_{CM} = \pm 2\frac{\Delta R}{R} \quad \text{for } R_1 = R_2}$ gives

a common-mode voltage gain of

$A_{CM} = \pm 2(0.1\%) = \pm 2(0.001) = \pm 0.002$

This is the variation that you will get for the common mode and the CMRR is A_v by A common mode. It is 1 by 0.002. That is equal to 500.

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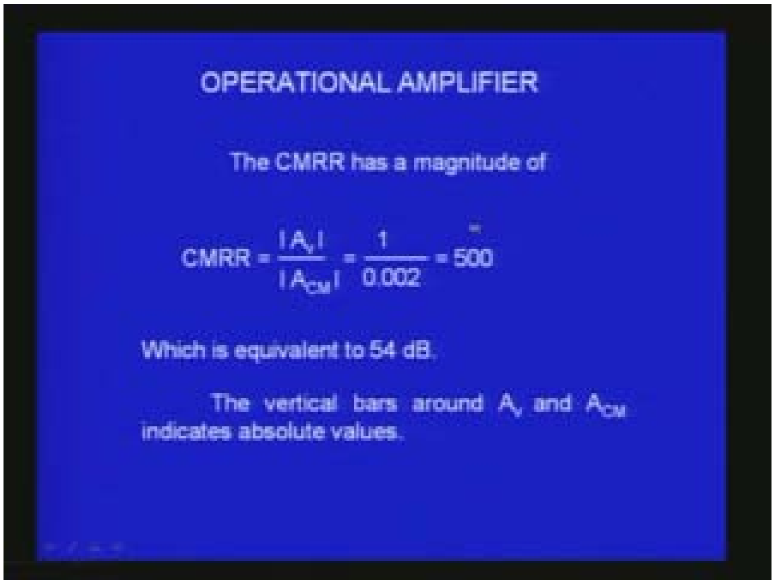

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The CMRR has a magnitude of

$$\text{CMRR} = \frac{|A_v|}{|A_{CM}|} = \frac{1}{0.002} = 500$$

Which is equivalent to 54 dB.

The vertical bars around A_v and A_{CM} indicates absolute values.

This 500 in numbers is equal to 54 dB. The vertical bar here shows that it is absolute values of the gain we are using without worrying about the sign. 54 dB is the CMRR magnitude. It has come down because of the tolerances of the resistors when I used 1% resistor. In spite of these problems still this configuration of a very simple differential amplifier like a subtractor basically it is a subtracting amplifier is one of the best simplest method of handling instrumentation signals, signals coming from very low levels and if at all you want to build a better instrumentation amplifier what we have to do is you should try to improve this configuration.

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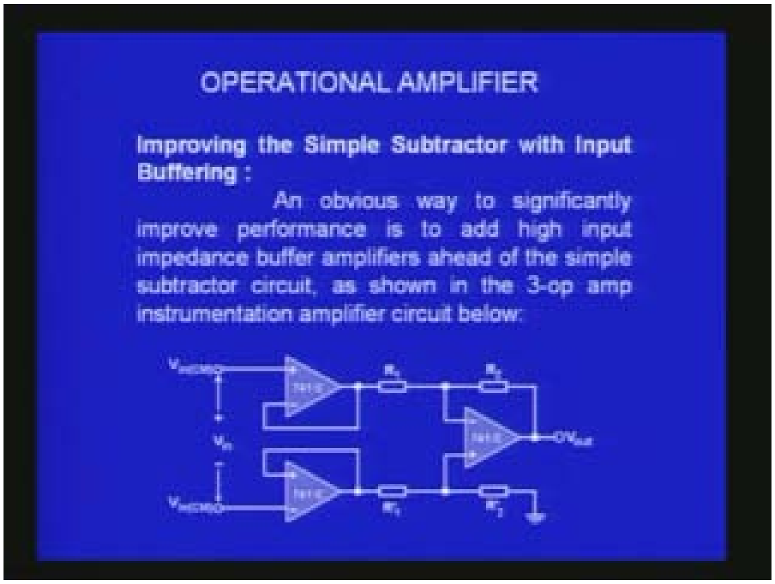

OPERATIONAL AMPLIFIER

Improving the Simple Subtractor with Input Buffering :

An obvious way to significantly improve performance is to add high input impedance buffer amplifiers ahead of the simple subtractor circuit, as shown in the 3-op amp instrumentation amplifier circuit below:

One way to improve this configuration is by using buffers. The instrumentation amplifiers will have different impedances corresponding to the two inputs inverting and non-inverting. First let us try to as address that issue and see how we can make the two impedances almost equal and large. One way to do that is to use a unity gain buffer. We have used a unity gain buffer corresponding to both the inputs one for the inverting input and another for the non-inverting input and instead of giving directly to this differential amplifier at the inputs we have added two unity gain buffers. The unity gain buffer has got very high input impedance; non-inverting buffers and they have very high input impedance and they will be almost be the same order in terms of input impedance because very very large the difference is very, very small between them and that takes care of the differences in the input impedance of the second stage which is the normal differential amplifier that we discussed about. This three op amp configuration of the instrumentation amplifier is very, very useful. We will apply in many situations. We will also see a demonstration at the end of a very similar configuration.

You can also improve further this configuration. What we have done here is for the earlier buffer we have made unity gain. You can also have a gain. In case you want you can improve that by adding an additional gain. That is what is shown now on the screen

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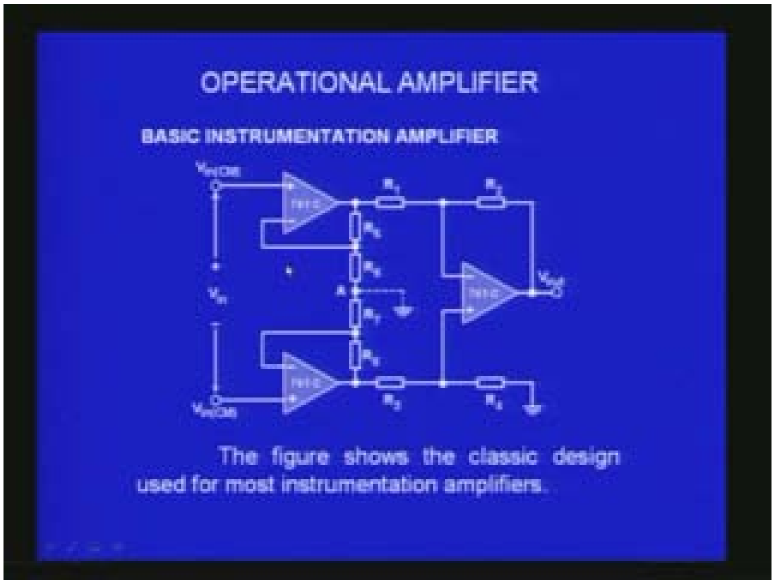

OPERATIONAL AMPLIFIER

BASIC INSTRUMENTATION AMPLIFIER

The figure shows the classic design used for most instrumentation amplifiers.

Here it has become now a non-inverting amplifier with R_5 and R_6. Similarly for the second input R_7 R_8 forms another combination which will make the second input also a non-inverting amplifier with a specific gain. The gain of the inverting input is 1 plus R_5 by R_8 and for the other one 1 plus R_8 by R_7. This will provide additional gain. You can have these resistors reasonably the same. For example R_5 and R_8 can be same R_6 and R_7 can be same. Thereby you would have the same gain for the two input amplifiers and then that amplified differential voltage will be applied to the difference amplifier which is coming as the second stage. This is one of the classic designs of the instrumentation amplifier.

Let us assume that R_5 is equal to R_8; R_6 is equal to R_7 and as before R_1 is equal to R_3 and R_2 is equal to R_4. R_1 is equal to R_3; R_2 is equal to R_4. Try to maintain all the resistors equal as much as possible so that the whole thing becomes simple to understand.

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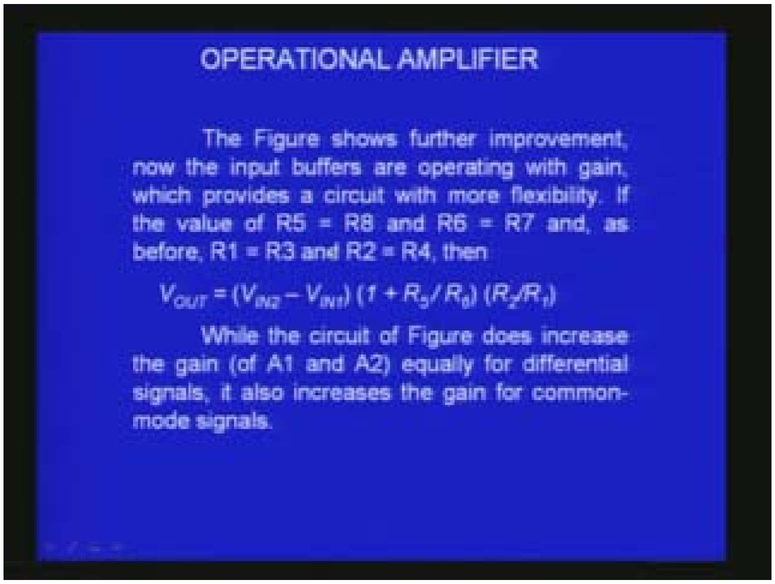

OPERATIONAL AMPLIFIER

The Figure shows further improvement, now the input buffers are operating with gain, which provides a circuit with more flexibility. If the value of R5 = R8 and R6 = R7 and, as before, R1 = R3 and R2 = R4, then

$$V_{OUT} = (V_{IN2} - V_{IN1})\,(1 + R_5/R_6)\,(R_2/R_1)$$

While the circuit of Figure does increase the gain (of A1 and A2) equally for differential signals, it also increases the gain for common-mode signals.

V output then will be the difference in voltage V_{in2} minus V_{in1} multiplied by 1 plus R_5 by R_6 into R_2 by R_1. Previously we had only R two by R one because we did not have the non-inverting gain stages at the input. Because we have a non-inverting gain stage and because the gains are the same for both the inputs we have 1 plus R_5 by R_6 coming there which is now coming as a product and there is a sign change here to take care of the minus sign that we get from the amplifiers. This does increase the overall gain because you have got additional gain stages at the input and the overall differential gain also will increase but at the same time the common mode signals also will get amplified by the two amplifiers. That is what we should remember.

Another modification of that is you replace the two independent resistors that are used here. R_6 and R_7 we used and we replaced it by one single R_G. That R_G will be R_6 plus R_7. That is what we used and if we use all of them equal then R_G will be twice that resistor that we used here.

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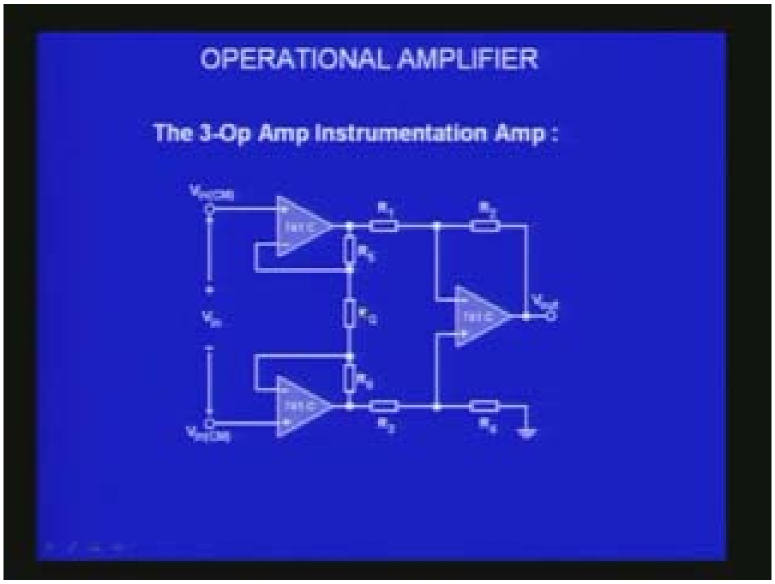

OPERATIONAL AMPLIFIER

The 3-Op Amp Instrumentation Amp :

This again is a slight modification of the earlier circuit and this also is a very good configuration for instrumentation amplifier. This provides a further refinement and therefore it becomes a very popular design. What is the important improvement? Improvement is the two resistors R_6 and R_7 are replaced by one single resistor R_G and that R_G can be varied to vary the gain or differential gain of the amplifier.

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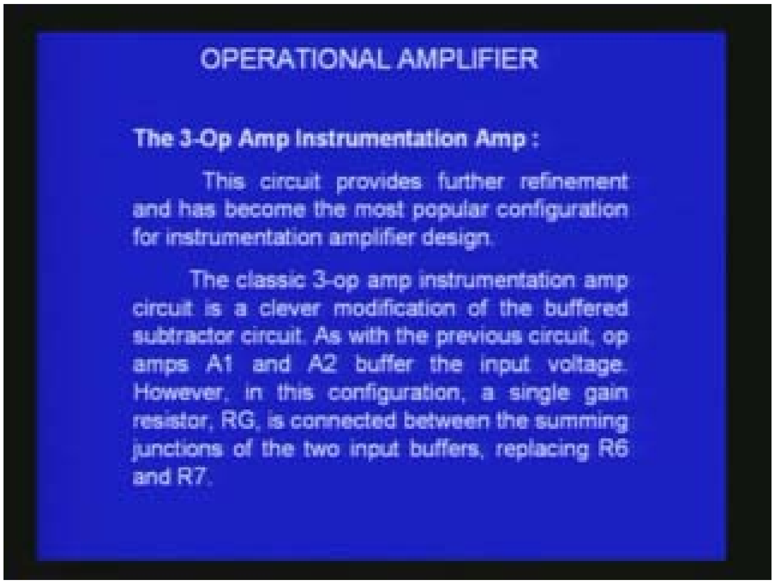

OPERATIONAL AMPLIFIER

The 3-Op Amp Instrumentation Amp :

This circuit provides further refinement and has become the most popular configuration for instrumentation amplifier design.

The classic 3-op amp instrumentation amp circuit is a clever modification of the buffered subtractor circuit. As with the previous circuit, op amps A1 and A2 buffer the input voltage. However, in this configuration, a single gain resistor, RG, is connected between the summing junctions of the two input buffers, replacing R6 and R7.

A_1 A_2 which are the gain stages for the input buffer amplifiers will make sure that the voltage here is same as the voltage here. In any op amp the two inputs should be almost equal to each other. This will be the same; this here is the same. The common mode signals will appear across R_6 but what is amplified will come here and the differential input will come between these two inputs which will be amplified by the second stage of difference amplifier. If I now vary the R_6 I will be able to vary the gain easily. This will also vary the common mode signal. This resistor can be used to vary the CMRR of the amplifier also. The full differential input voltage will now appear across R_G because the voltage at the summing junction of each amplifier is equal to the voltage applied to its positive input.

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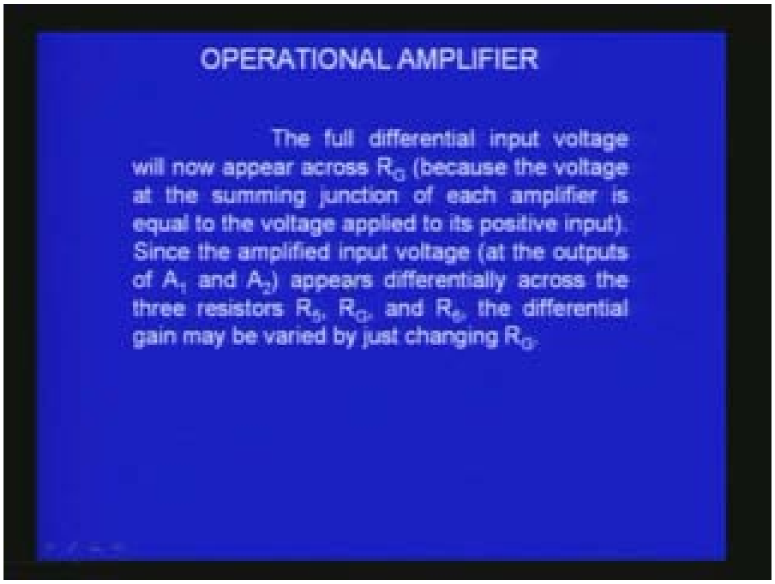

OPERATIONAL AMPLIFIER

The full differential input voltage will now appear across R_G (because the voltage at the summing junction of each amplifier is equal to the voltage applied to its positive input). Since the amplified input voltage (at the outputs of A_1 and A_2) appears differentially across the three resistors R_5, R_G, and R_6, the differential gain may be varied by just changing R_G.

Since the amplified input at the output A_1 and A_2 appears differentially across the three resistors R_5, R_G and R_6 the differential gain may be varied by just changing R_G. That is one of the advantages of this circuit. Having talked about the various instrumentation amplifiers and their refinement, what will be the applications of these amplifiers? They are useful in instrumentation amplifiers. One of the simplest applications that I can think of is a sensor. I have a sensor which is basically a resistive sensor; for example light dependent resistor. The resistance varies depending upon the intensity of light falling on it or you have a thermistor where the resistance depends on the temperature or you have a strain gauge where the resistance depends on the stress applied on the system. All these are resistive transducers or resistive sensors. If I have resistive sensors the best way is to convert the variation in resistance into voltage which is what we want; we would like to have. Because we can amplify voltages using amplifiers we would like to convert the change in resistance due to the various parameters like light or temperature or strain into useful voltage, sensed voltage and then amplify them. When you have such a problem the best and the simplest technique is to put them in a normal well known Wheatstone bridge configuration where you have four arms R_1, R_2, R_3, R_4 and R_1 by R_2 is equal to R_3 by R_4. When the bridge is balanced the output voltage is zero. When there is an imbalance in the bridge due to a variation of one arm of the bridge you get a corresponding voltage output which can be amplified and if the variation is produced due to temperature or light intensity or stress or strain you will get correspondingly an output which is proportional to that variation and you are able to measure the temperature or the light intensity or the strain. That is the principle of the bridge amplifier where the bridge amplifier is basically a differential amplifier and better thing would be to use an instrumentation amplifier.

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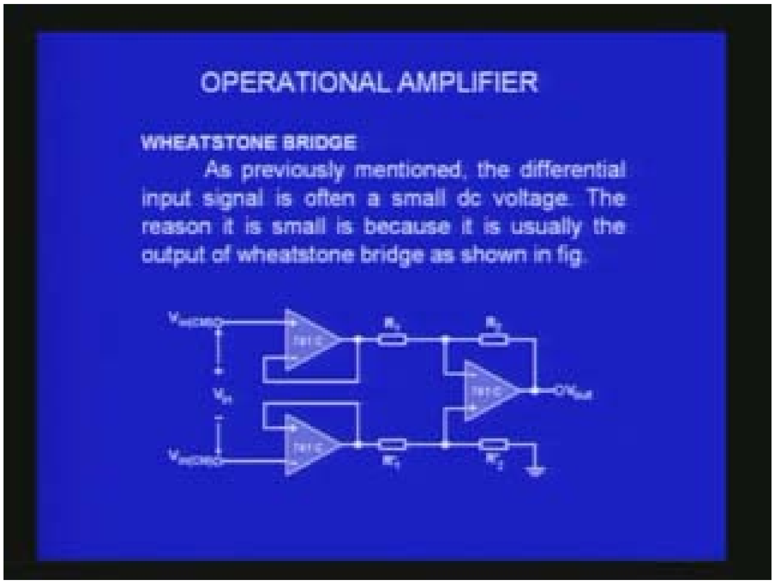

OPERATIONAL AMPLIFIER

WHEATSTONE BRIDGE

As previously mentioned, the differential input signal is often a small dc voltage. The reason it is small is because it is usually the output of wheatstone bridge as shown in fig.

I have shown on the screen how you can connect a Wheatstone's bridge here corresponding to the simple differential input configuration corresponding to an instrumentation amplifier that we discussed.

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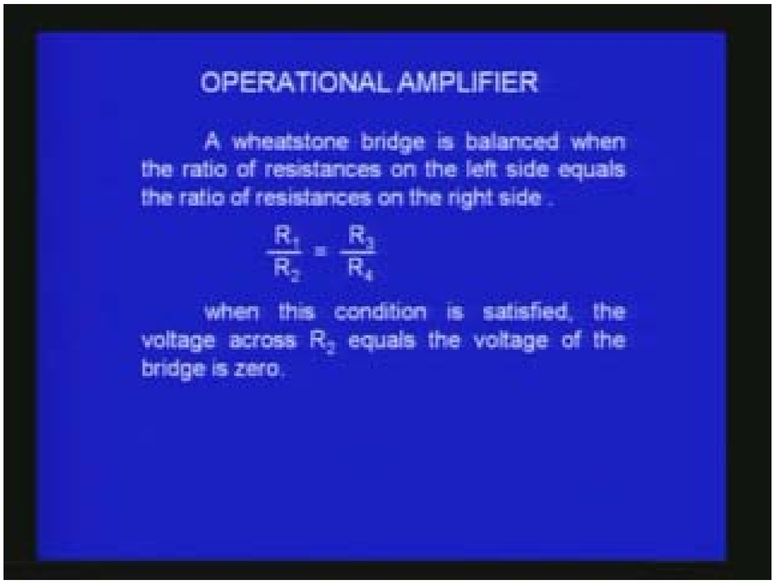

OPERATIONAL AMPLIFIER

A wheatstone bridge is balanced when the ratio of resistances on the left side equals the ratio of resistances on the right side .

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

when this condition is satisfied, the voltage across R_2 equals the voltage of the bridge is zero.

In the Wheatstone network R_1 by R_2 is equal to R_3 by R_4. If any one of the resistor is going to change due to some parameters being a sensor or a transducer then the output of the amplifier will become proportional to that parameter.

I have given lot of examples of those transistors and now I am showing you the complete circuit where I have this bridge here connected to +15 and minus ground across the diagonal points and then the other diagonal point will be connected as the input for your instrumentation amplifier which is again a three op amp instrumentation amplifier configuration.

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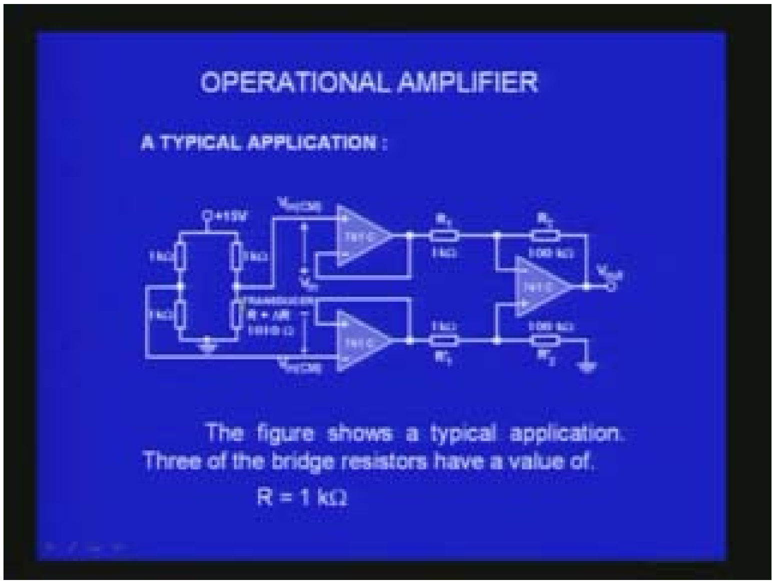

OPERATIONAL AMPLIFIER

A TYPICAL APPLICATION :

The figure shows a typical application.
Three of the bridge resistors have a value of.
R = 1 kΩ

Typically in this circuit I have taken all the resistors to be 1K, 1K, 1K and only one of them which is a transducer I have chosen to be one k and it can vary by plus or minus delta R where the resistance change is proportional to the temperature and that is what I have shown here in the circuit and the output will now be a differential input which is proportional to the change in resistance and it will also have a common mode voltage which is going to be 15 volts divided by two resistors of almost equal value. The common mode voltage here will be around 7.5 half of 15 volts and here also it will be very close to that except for the variation that is going to come due to the change in the parameter either temperature or light. That is going to be amplified here and because this has got good CMRR configuration, this will preferentially amplify only the change in the resistance here assuming these resistors are very precise within 0.1 or 0.01% tolerance.

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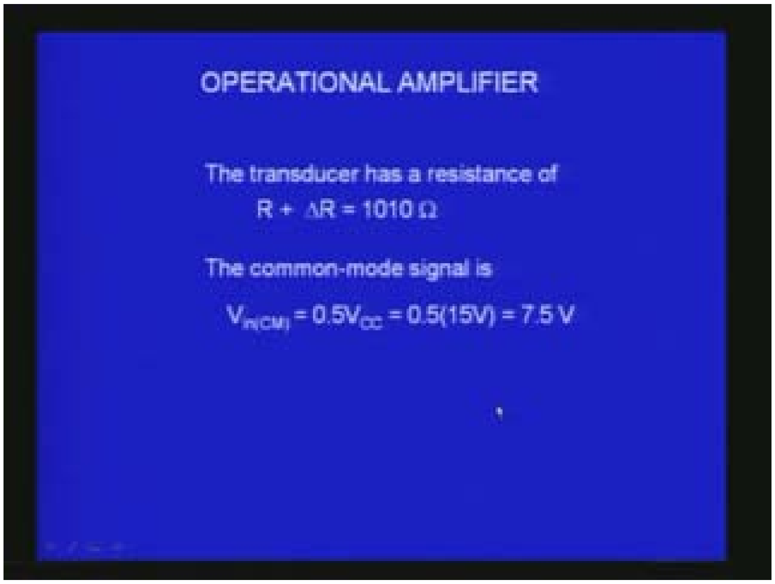

OPERATIONAL AMPLIFIER

The transducer has a resistance of

$R + \Delta R = 1010\ \Omega$

The common-mode signal is

$V_{in(CM)} = 0.5V_{CC} = 0.5(15V) = 7.5\ V$

The common mode input is 0.5 times. Because we have used two 1K resistors across 15 volts it will be 7.5 volts.

I will show you an actual circuit which is formed by three op amp with two buffers and one difference amplifier. The other important point which I did not mention is that it is always convenient to have even the buffer amplifiers all in one single monolithic IC rather than using three independent operational amplifiers. Instead of using three op amps I have actually made use of LM 324 which is a quad op amp. Four op amps are there in that and I have used three op amps for our purpose, for building an instrumentation amplifier. The advantage of having a single operational amplifier array is because the two input buffer op amps also are very close to each other they will have very good tracking characteristics. Their temperature differences, etc will be very well taken care of because they will become common mode signal now. They are very close to each other and so anything that is common will be rejected by the difference amplifier and if they are on the same monolithic chip then it becomes all the more better in terms of performance. The suggestion is instead of using 3 independent operational amplifiers it will be a good idea to use one singe IC which has got either 3 or 4 op amps and make use of 3 op amps for the instrumentation amplifier configuration.

I will quickly move over to the demonstration table and show you the working of a similar instrumentation amplifier configuration. The circuit is shown here. It has got 3 op amp configuration with R_G here and it is also having a gain here which is shown by R prime, R_1, etc.

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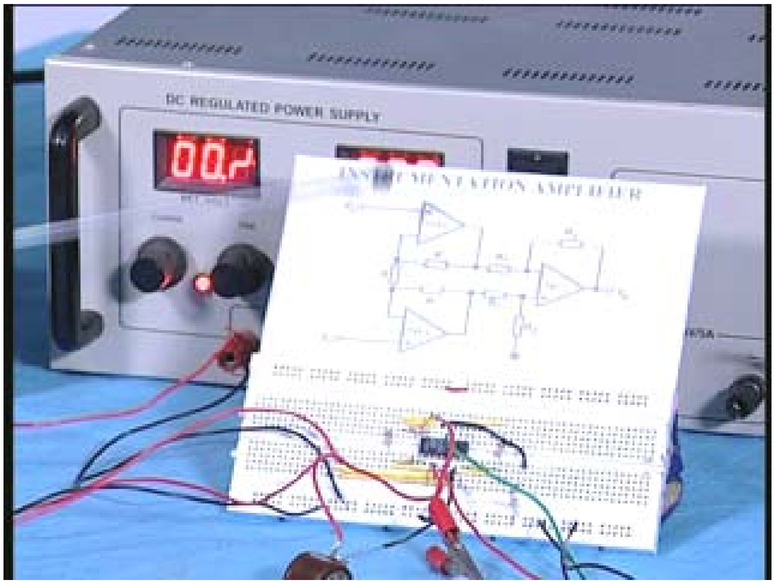

I have two op amps here and the third op amp is a normal differential amplifier and the input is given from a millivolt source which is seen here. This is a standard millivolt source which we have been using in all our experiments and that is connected as the input here and the output is monitored by making use of the multimeter and we have a dual supply at the back which is providing the voltage for the circuit that you see here. I would like to show you also the circuit here. This is the LM324 quad operational amplifier circuit and the various resistors and wiring is done exactly according to this configuration and one of the resistors the R_G is at the middle; these two R prime and this they three come together and this is the potentiometer which is being used as the variable thing for changing the gain and the CMRR of the instrumentation amplifier configuration. The input is around 500 millivolts. If you see the multimeter it shows about 0.49 nearly about 500 millivolts or 0.5 volts.

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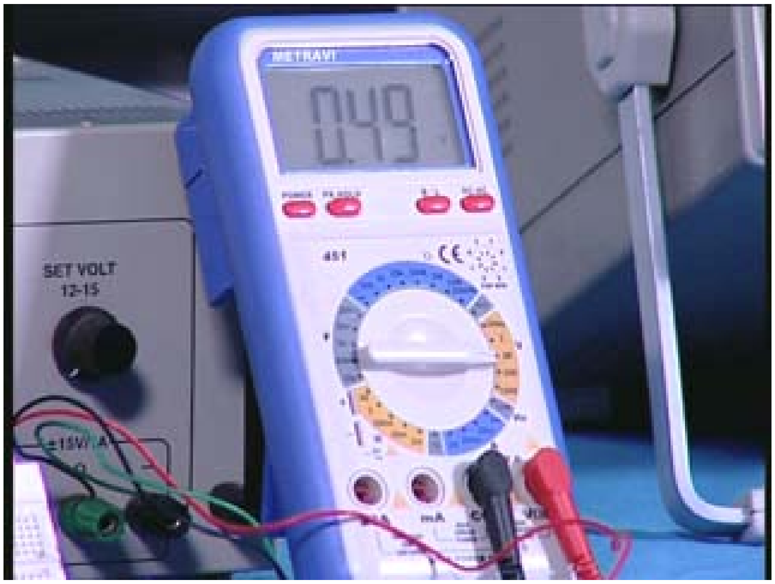

Let us measure the output. Output is around 0.2 because this resistance is in the lowest position.

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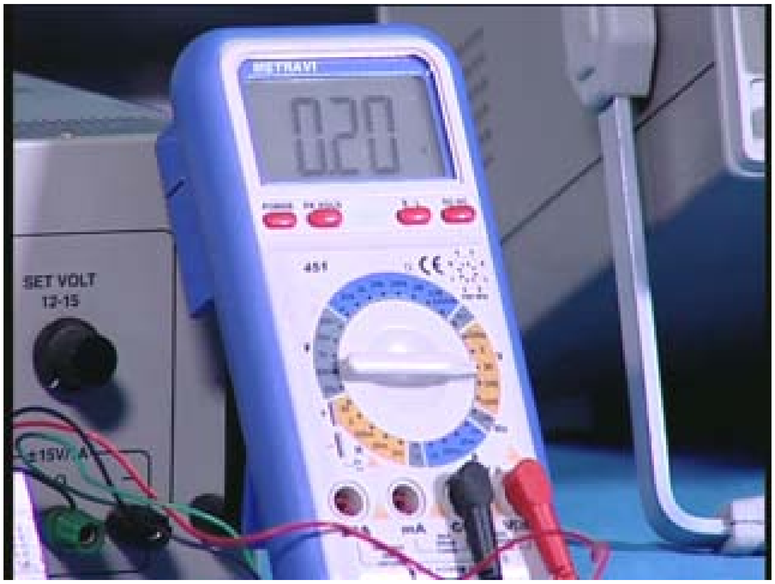

Now I am going to increase the resistance. As I increase the resistance on the multimeter the voltage is changing correspondingly. When I increase it goes to 0.49 which is the maximum you can get corresponding to the resistors that I have used. I have used a gain of 1 and therefore you get point 0.49. R_2 by R_1 everything is 10K here and you get a gain of 1. By making use of this potentiometer you will be able to change the gain and you can use this simple configuration as the instrumentation amplifier.

Having seen this application of the operational amplifier which is as an instrumentation amplifier we will move on to another application of the operational amplifier which is for driving larger currents. In most of the applications especially for example if you want to drive a solenoidal valve or wall? or a motor we not only have to amplify the voltage but we should also have enough current drive capacity for driving the motor or the solenoidal valve. Unfortunately if you take the 741 operational amplifier the short circuit current is around 25 milli amperes typically.

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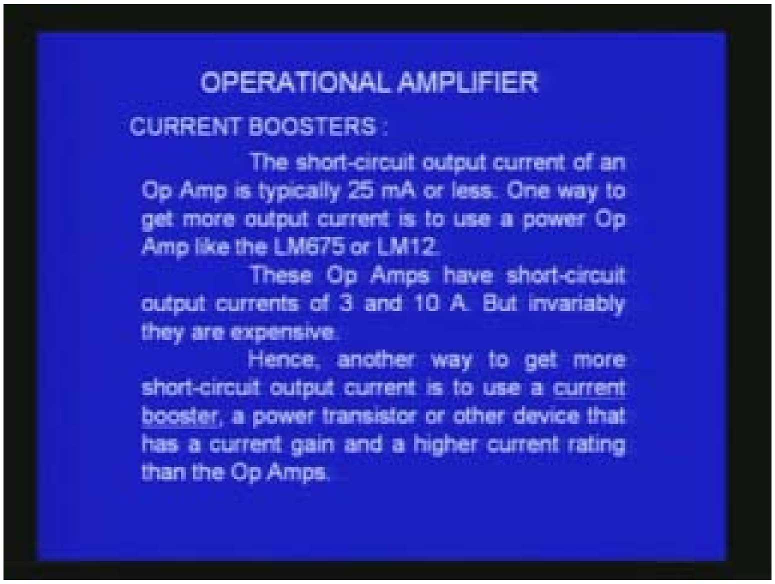

OPERATIONAL AMPLIFIER

CURRENT BOOSTERS :

The short-circuit output current of an Op Amp is typically 25 mA or less. One way to get more output current is to use a power Op Amp like the LM675 or LM12.

These Op Amps have short-circuit output currents of 3 and 10 A. But invariably they are expensive.

Hence, another way to get more short-circuit output current is to use a current booster, a power transistor or other device that has a current gain and a higher current rating than the Op Amps.

That means what? Even if I connect the output of the operational amplifier to the ground I will get maximum of 25 milli amperes. If you keep it for long the operational amplifier will be burnt out but that gives also on a limit to the maximum current that I can obtain from operational amplifier. That is rather low 25 milli amperes. If I want more output current of the order of several hundreds of milli amperes or even amperes then you have to go for power op amps. There are power op amps available. For example I have given two typical numbers LM675 or LM12. There are plenty from different manufacturers. You can refer to different data manuals and try to look for power op amps and then find the maximum current they can handle. But I can assure you that they are rather expensive.

Is there a way by which I can use the same 741 which is rather inexpensive, simple to operate, very familiar to us also but at the same time improve its current performance; its performance with reference to output current? The answer is yes and you can use a very simple scheme and that is by using an additional transistor, a power transistor. If we use a power transistor which can handle higher current in combination with 741 operational amplifier then you can go to higher currents than 25 milli amperes. You can even go to 3 amperes or 10 amperes and that way it becomes very inexpensive because power transistors are not all that expensive. 741 is also not very expensive and when I combine them I will be able to get much higher currents for not very expensive scheme. This I call the current boosters. We can have a very simple configuration. I am going to talk about two types of current boosters. One is uni directional current booster which is mostly used for some simple DC applications.

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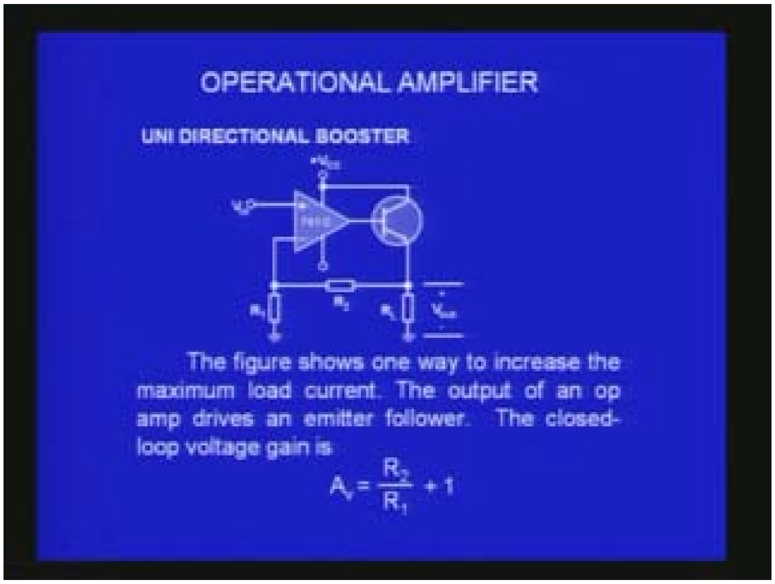

OPERATIONAL AMPLIFIER

UNI DIRECTIONAL BOOSTER

The figure shows one way to increase the maximum load current. The output of an op amp drives an emitter follower. The closed-loop voltage gain is

$$A_v = \frac{R_2}{R_1} + 1$$

I have shown a circuit here where I have used a op amp in the non-inverting mode and the base of the transistor which is a power transistor here is connected to the output of the operational amplifier and the collector of the n-p-n transistor is connected to the V_{cc} and the emitter is connected to the output point to which I can connect the load R_L. What I get across R_L is the V output and you have a V_{in} here and this R_1 R_2 forms a non-inverting configuration. The gain of the non-inverting amplifier is R_2 by R_1 plus 1 or 1 plus R_2 by R_1 and the output current from the op amp is used as the base current. The advantage of that is the transistor has its shown beta, the current gain, the hfe and this output current from the operational amplifier is only the base current. You have to multiply by beta times to obtain the collector or the emitter current. You have another factor coming in, multiplication factor which is able to boost the total current.

There is also another important point here to recognize and that is the emitter of the transistor is connected to the load. This is also very useful because if you want a good voltage amplifier the output of the voltage amplifier should be almost close to an ideal voltage source. That means its output impedance or output resistance should be very, very low. The moment I bring in a transistor how to maintain still low output impedance? Usually 741 has got low output impedance of the order of 75 ohms and when I connect a transistor I want to maintain that low resistance. For that what I do is I use a transistor in the emitter follower mode or the common collector mode. The emitter is connected to the load. Because of this there is going to be a reduction in the output impedance and you also have a feedback, negative feedback. That also will bring down the output impedance.

That is what I have shown here. Z output is going to be Z output of the normal amplifier divided by 1 plus A beta where A is the gain, B is the feedback ratio.

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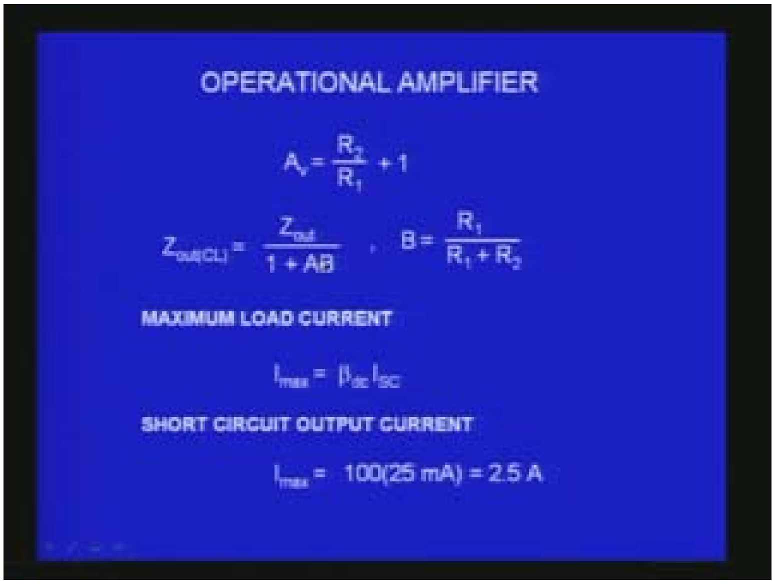

OPERATIONAL AMPLIFIER

$$A_v = \frac{R_2}{R_1} + 1$$

$$Z_{out(CL)} = \frac{Z_{out}}{1 + AB} \quad , \quad B = \frac{R_1}{R_1 + R_2}$$

MAXIMUM LOAD CURRENT

$$I_{max} = \beta_{dc} I_{SC}$$

SHORT CIRCUIT OUTPUT CURRENT

$$I_{max} = 100(25\ mA) = 2.5\ A$$

B in this case, because you have used R_1 and R_2, is R_1 divided by R_1 plus R_2. The maximum load current I_{max} is beta- B is in the slide not beta times the I which is the short circuit current; the maximum current that I can get from the op amp and beta dc if I assume to be 100 for the transistor the beta for the transistor is 100 then I short circuit is typically 25 milli amperes. When you multiply that you can get 2.5 amps. Just by introducing a power transistor which has got a current gain of about 100 you are able to improve the short circuit current or the maximum current that you can get from your op amp amplifier configuration from a simple 25 milli ampere to 100 times more; 2.5 amperes. This is a very, very useful circuit for driving solenoid valves and coil motor. I will show you the current boosting circuit.

This is the same circuit which I just now showed you. It is a non-inverting amplifier. The non-inverting input is the input for the voltage and you have R_1 and R_2 connected. This is 1K and this is 10K. There is a gain of 1+10/1. That is 11 and 1K is also the load here presently connected. This is the transistor and the transistor in the circuit is SL100. This is a SL100. This is op amp and the wiring is done exactly for this configuration. I have got here three resistors because I wanted to show for three different resistors the output voltage. I do have same 500 millivolts as my input voltage from that millivolt source. I have 500 millivolts as the input coming to the amplifier.

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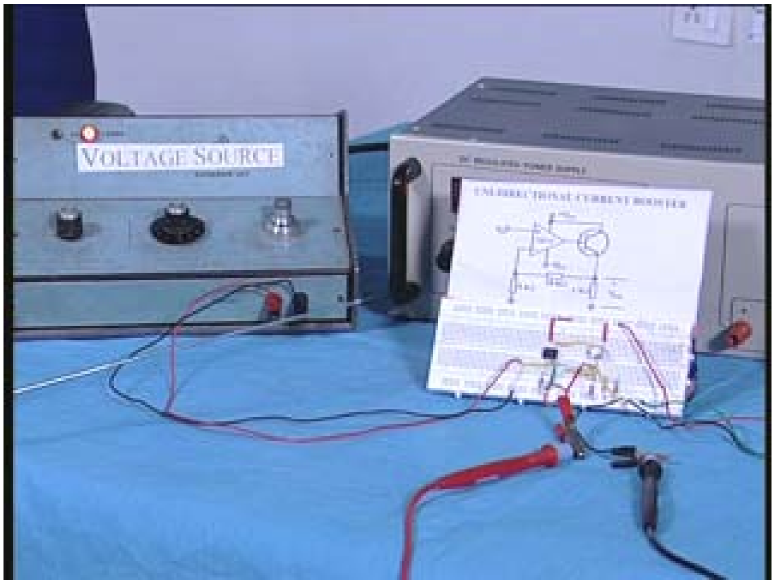

The output of the amplifier is monitored by using a digital multimeter which shows 5.63. That is a gain of 10 times; eleven times nearly 55. 500 multiplied by 11 is 5.5 volts. There is already a gain here.

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5.63 is very close to 5.5. The additional voltage is due to other aspects like the offset voltage and input bias current variations. Now what I am going to do is I am going to vary the load and show you. Now I have connected 1K. What I have done is I have removed the 1K resistor and I have connected a 470 ohm resistor as the load. As I change the load the voltage should not change the output voltage should remain constant. It is still 5.62 even when I change the load to a lower value nearly half of the previous value. Again I am going to change that to a different value that is a larger value. This is around 2.2K. This is 10K resistor that I have connected here as the load and even now the voltage is not very different. It is only slightly less, 5.8.

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There will be a limit as to how far we can go. If we go to large resistors then it will create problem. Within a range even if you change the load the output voltage remains a constant. That obviously shows the output behaves more like a voltage source and whatever is the input that is what I get at the output. Now I am going to slightly increase the input voltage also from 500 to 600 and the output voltage also is changing correspondingly.

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If I still increase it goes to a new value nearly 8 volts and if I now bring it down correspondingly the output voltage also decreases. Again it is 500 and it comes back to 5.8; at the output at the output is 5.8. Still further I decrease; it is now 400 millivolts and it is around 4.7. The output varies according to the input voltage whenever I change the voltage. But if I change the load by a range the output does not change at all. It remains constant. That shows that this is a very good output driving stage and because the load comes in the emitter of the transistor it becomes an emitter follower configuration and thereby it produces a very low impedance and therefore very useful.

Having done this unidirectional current booster what will happen if I have a sinusoidal input? Not a dc but an ac input. Can I still have a drive which will be able to provide much higher current than what a simple operational amplifier can give? This operational amplifier can give only above 25 milli amperes as a short circuit current. Let us try to modify the circuit to take care of the variations of the voltage on both sides. Even then you must have a large current provided both on the positive and the negative side. You can see on the screen a simple configuration. It is cleverly constructed with two transistors. One is npn the other is pnp in what is known as a push pull configuration or in this case it is a complementary transistor. One is the npn and the other is the pnp. Both the emitters are connected together and that is connected to the load R_L and the collectors of the two transistors are maintained at positive and negative voltages, plus and minus corresponding to the transistor.

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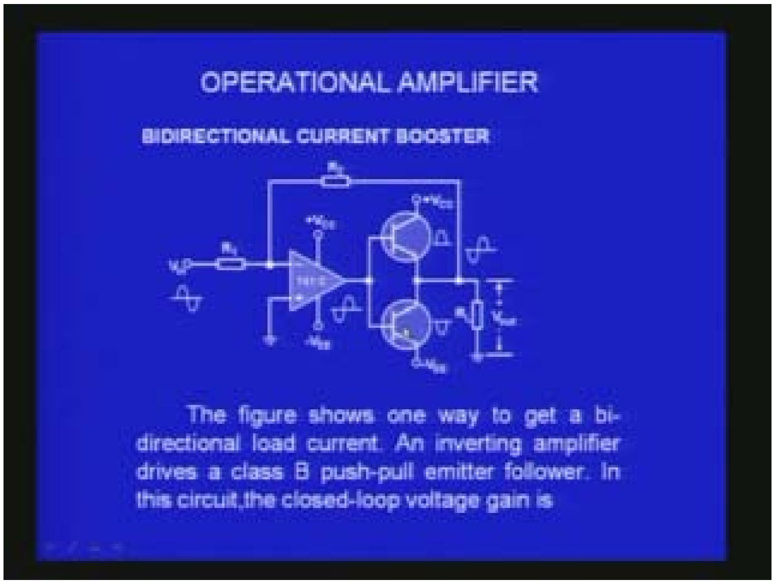

OPERATIONAL AMPLIFIER

BIDIRECTIONAL CURRENT BOOSTER

The figure shows one way to get a bi-directional load current. An inverting amplifier drives a class B push-pull emitter follower. In this circuit,the closed-loop voltage gain is

The output of the operational amplifier is connected in parallel to the two base of the transistors and the feedback comes to the emitter of the transistor. This is R_1 by R_2. This is an inverting configuration. In this case for a change the non-inverting input is grounded. The inverting input has R_2 and R_1 as the resistors so that amplifier gain will be $–R_2$ by R_1. There will be a phase difference at the output as shown in the sign and because we now have two transistors when a signal goes positive the current will be drawn in this direction and when the signal goes negative the current will be drawn by the second transistor in the reverse direction. Both sides the current can swing with reference to the R_L load and it has got all the good features of the previous circuit which I showed as the current booster for uni directional outputs because again here the load is at the emitter of the two transistors. It continues to remain in the emitter follower configuration which always gives you low impedance at the output.

What I am now going to show is a very similar circuit which is also called as push pull emitter follower and it is in the class b operation and this closed loop voltage gain is $–R_2$ by R_1 because it is an inverting amplifier and the output closed loop impedance will be Z output divided by 1 plus A beta where A is the gain of the amplifier, beta is the feedback ratio. Beta is R_1 by R_1 plus R_2 and A is $–R_2$ by R_1 you can calculate and then correspondingly find out how much is the improvement and the maximum load current again is the same as beta dc into I_{sc}.

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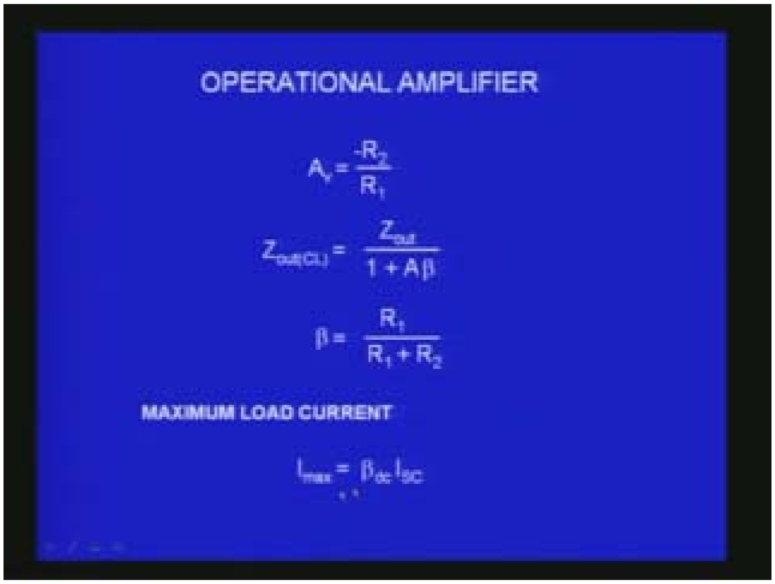

OPERATIONAL AMPLIFIER

$$A_v = \frac{-R_2}{R_1}$$

$$Z_{out(CL)} = \frac{Z_{out}}{1 + A\beta}$$

$$\beta = \frac{R_1}{R_1 + R_2}$$

MAXIMUM LOAD CURRENT

$$I_{max} = \beta_{dc} I_{SC}$$

The maximum load current is the beta or the current gain of the transistor multiplied by the short circuit current. We assume the beta for both the transistors to be identical which is normally true. If it is a matched pair the two transistors will have the same beta. So it becomes very useful. I have shown with the simple example.

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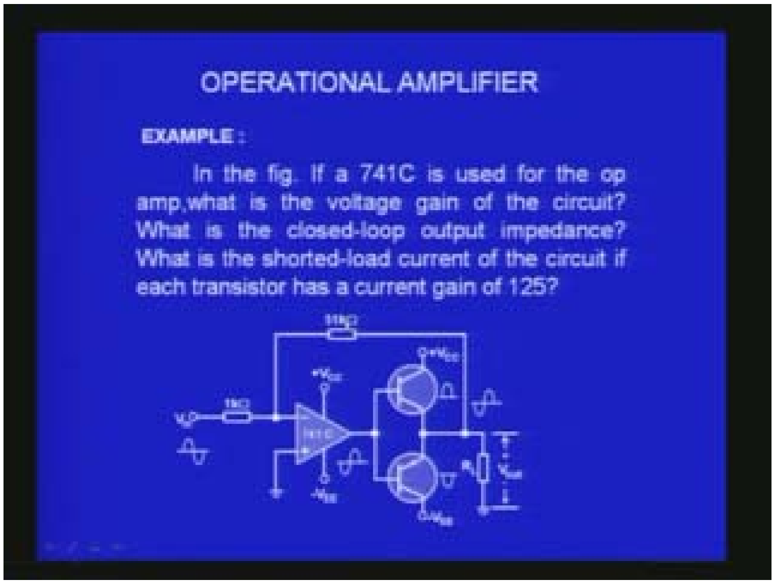

OPERATIONAL AMPLIFIER

EXAMPLE :

In the fig. If a 741C is used for the op amp,what is the voltage gain of the circuit? What is the closed-loop output impedance? What is the shorted-load current of the circuit if each transistor has a current gain of 125?

I have got 51 kilo ohm resistor here and 1 kilo ohm. Therefore the gain is around 50. In the figure if 741C is used for the op amp what is the voltage gain of the circuit? What is the closed loop output impedance and what is the short circuit load current of the circuit if each transistor has got a gain of 125? It is a small typical numerical example.

The gain is –R_2 by R_1; voltage gain is -51 by 1 that is 51.

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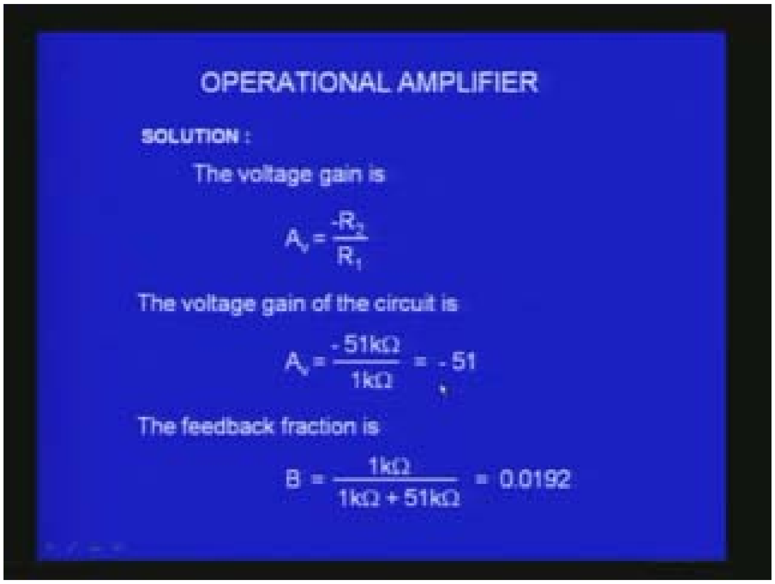

OPERATIONAL AMPLIFIER

SOLUTION :

The voltage gain is

$$A_v = \frac{-R_2}{R_1}$$

The voltage gain of the circuit is

$$A_v = \frac{-51k\Omega}{1k\Omega} = -51$$

The feedback fraction is

$$B = \frac{1k\Omega}{1k\Omega + 51k\Omega} = 0.0192$$

Feedback is 1 by 1 plus 51; that is equal to 0.0192 and if the typical value of the output resistance is 75 ohms for 741 it is 1 plus A beta. A is 100,000 typical value of the gain multiplied by the beta 0.0192 and that is 0.039 ohm which is very, very small due to the feedback and the maximum current is 25 into 125; 125 is the beta of the transistor. If we multiply it is 3.13 amperes.

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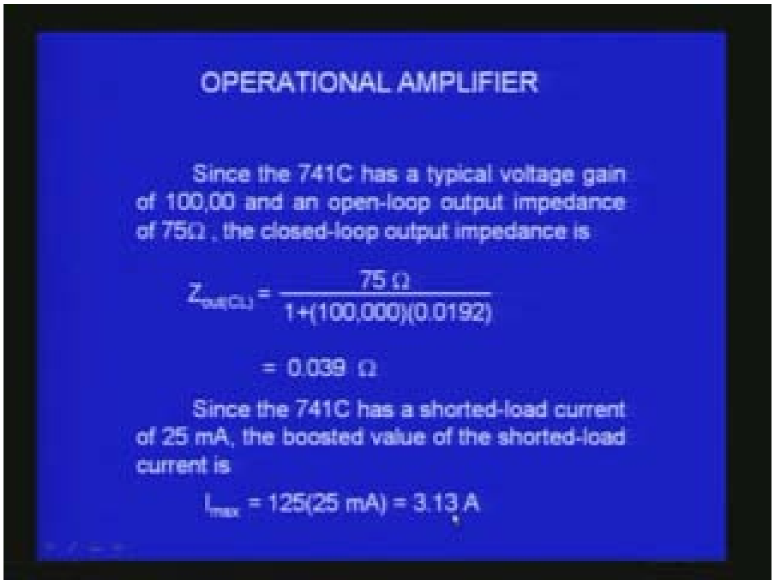

OPERATIONAL AMPLIFIER

Since the 741C has a typical voltage gain of 100,00 and an open-loop output impedance of 75Ω , the closed-loop output impedance is

$$Z_{out(CL)} = \frac{75\ \Omega}{1+(100,000)(0.0192)}$$

$$= 0.039\ \Omega$$

Since the 741C has a shorted-load current of 25 mA, the boosted value of the shorted-load current is

$$I_{max} = 125(25\ mA) = 3.13\ A$$

You get very low output impedance and you also get a very high current 3.13 amperes.

This circuit is very, very useful in several power amplifier circuit applications. We will see the demonstration now. The circuit here is exactly same as the one which we discussed a moment ago. This is a 1K resistor; here 51. Here it is actually 10 kilo ohm and the gain is 10; – R_2 by R_1. There is a minus that shows that there will be an inversion and you have the two transistors. This is SL100 and SK100.

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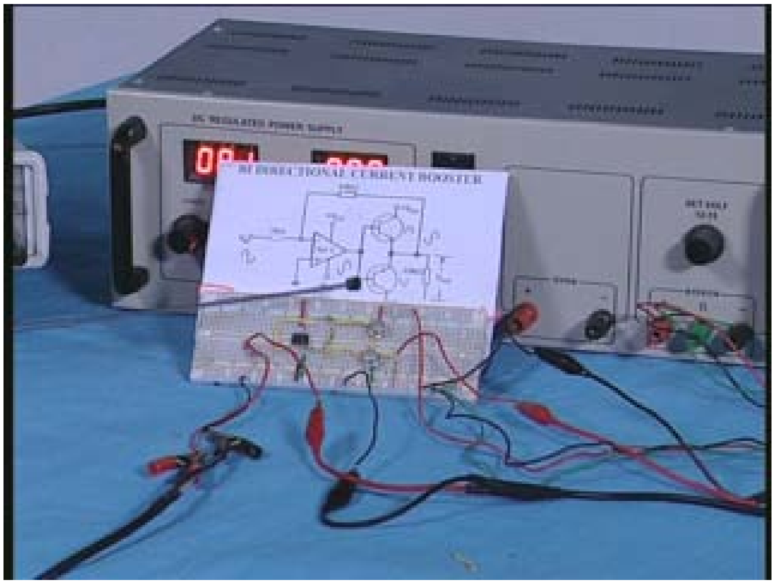

These are the matched pairs. If you want a higher current you can always go for other power transistors which can handle much higher currents and the emitters of the two are connected together and connected to a load here and the input is given from a function generator around 500 hertz. The frequency is about 533 hertz and that is the input given to the transistor and the output is monitored using an oscilloscope. The two waves are slightly separated and there is a 180 degree out of phase.

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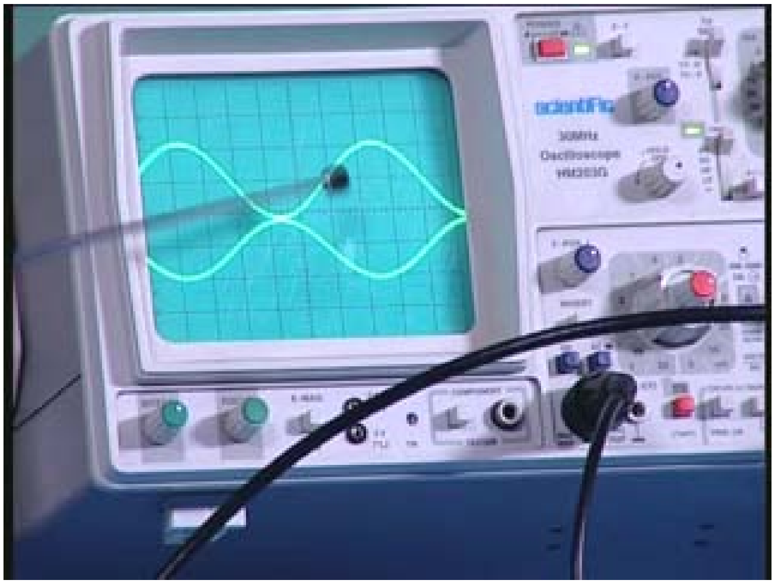

When one is decreasing the other one is increasing; when one is increasing the other is decreasing. There is a 180 degree out of phase because it is an inverting configuration and the amplitudes are almost same and the actual amplification ….. is about 10 times here in this; amplification factor. If I increase the amplitude correspondingly the output also changes. If I change here the output also changes.

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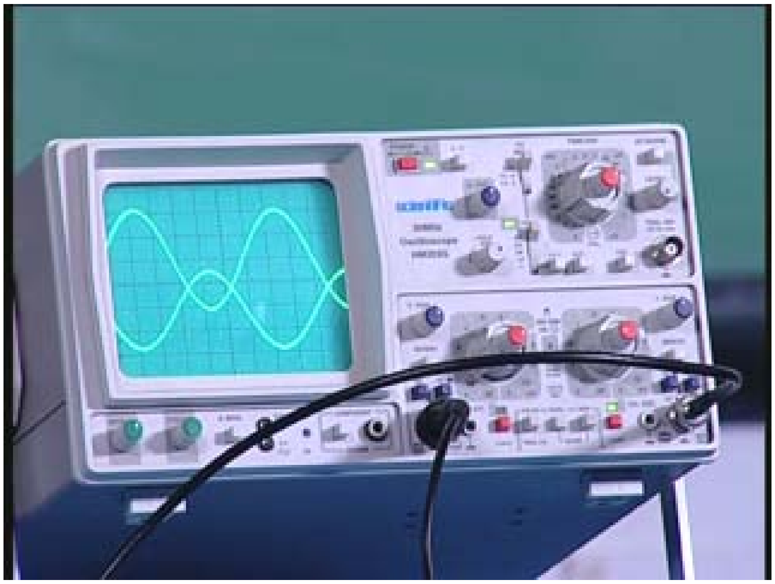

That means both sides the two transistors will automatically take care of the two swings of the input voltage to drive the load. The load here is around 1K. You can change this load to any relay or any higher solenoid valve and you will be able to drive it very easily up to about 2 amperes. This current booster is also very useful application.

Today we have seen in this lecture that you can build good three operational amplifier, instrumentation amplifier configuration for amplifying signals from sensors, resistive sensors in the form of wheat stone's bridge and we also saw two different configurations of current booster circuits. How the current output from a simple operational amplifier can be improved by using a past transistor either single npn transistor or a matched pair npn pnp combination in the push pull or complementary pair configuration and the emitter follower mode and thereby you will be able to improve the current capability of the amplifier. Thank you!