Analog ICs
Prof. K. Radhakrishna Rao
Department of Electrical Engineering
Indian Institute of Technology, Madras
Lecture - 17
Transconductance Operational Amplifier

In the last class we saw something about operational voltage amplifier, how the synthesis is done and how the analysis is made for any given op amp and how the important parameters are evaluated. In today's class we will discuss operational transconductance amplifier. It does not really matter what operational purpose for which it is going to be used addition, subtraction, integration, differentiation etc as long as the op amp has one of the four types of characteristic with forward transfer parameter being very high it can serve the purpose. So the second category which was prevalent for a long time, in fact this is not something that has come about recently, this particular configuration operational transconductance amplifier was in existence, particularly RCA had fabricated this op amp long ago even before the operational amplifier for MOS VLSI came into prominence.

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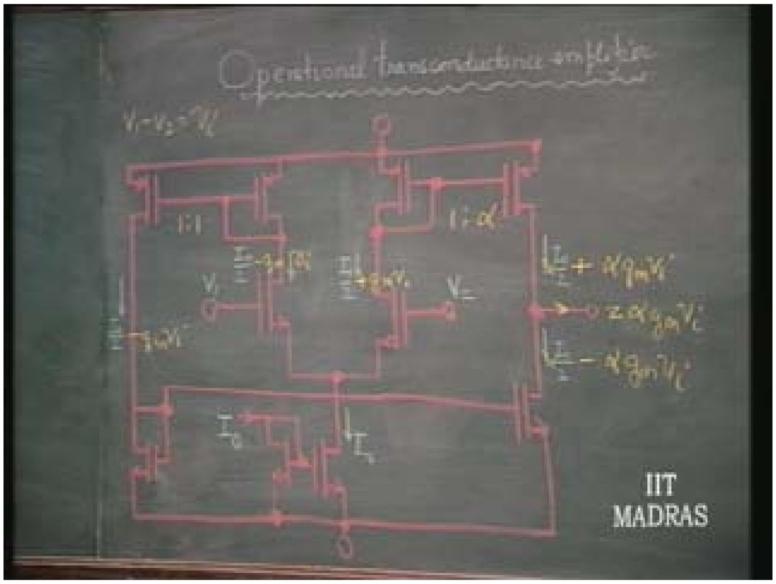

This was an SSI circuit which was using CMOS structure and the basis of this is again the differential amplifier. Here you can see differential amplifier at the input. Here V_1 minus V_2 is equal to V_i the differential input voltage, this is converted into signal current which is gm times V_i. We know how to evaluate the value of gm. Knowing the operating current of this transistor as I_0 by 2 we can evaluate the gm of the pair at the operating point.

So the change in current in this is I_0 by 2 minus gmV_i, I_0 by 2 plus gmV_i this being the constant current. This is the normal transfer of current that happens when I apply a voltage V_1 minus V_2 is equal to V_i. Now this current is made to go through current mirror. So this current is going to get reflected here as an identical current I_0 by 2 minus gmV_i using this current. This current I_0 by 2 plus gmV_i is again mirrored onto this side but with a w by l ratio corresponding to not 1:1 but 1:alpha in which case the current is going to be alpha times that. So a current boosting has occurred, so I_0 by 2 plus actually this is also going to be alpha I_0 that alpha is going to appear because of the ratio here, so alpha times I_0 by 2 plus alpha gmV_i plus alpha times I_0 by 2 minus alpha times gmV_i because this current again is reflected on to this side.

The current mirror from here is converted on to this side so now we have one current source another sink current source giving a current of alpha I_0 by 2 plus alpha gmV_i current sink which is alpha I_0 by 2 minus alpha gmV_i so the output current that is pumped out, this and this have the same ratio. Therefore these are the output transistors operating at alpha times I_0 by 2 higher current because of the w by l ratio being different, the k ratio being a bit different and this was the case with bipolar transistor current mirror.

By changing the area we could change the current ratio. So we have now obtained an output current which is two times alpha times gm into V_i and this is a current output. It can be in this direction or in that direction depending upon V_i. We can source current or sink current. So this is a true what transconductance type amplifier, output is a current source and input is a voltage. This voltage input Vi is converted into this kind of current output.

So what is the transfer parameter in this case?
It is 2 alpha gm, the transconductance is 2 alpha gm. In the operational voltage amplifier ideal parameter is g parameter. The g_{21} was voltage gain. And in an operational current amplifier ideal parameter was h parameter h_{21} was current gain. In this particular case it is the y parameter.

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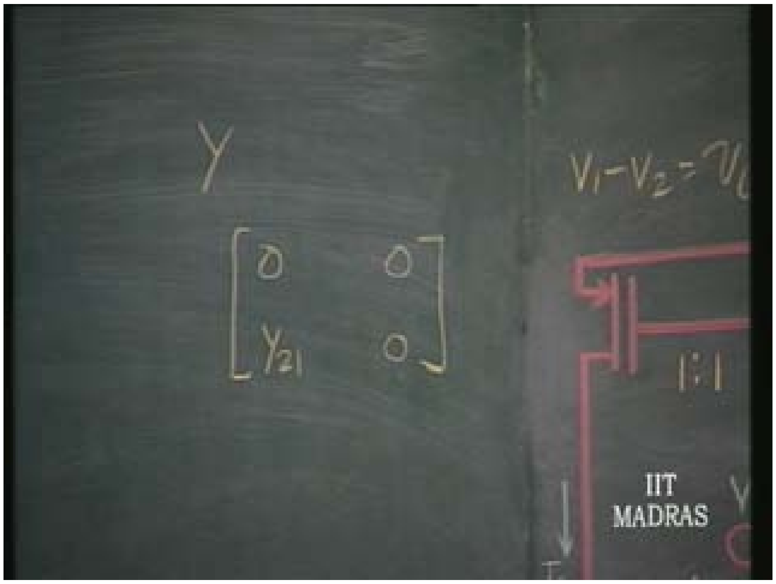

This is going to be expressed in terms of Y parameter, this is 0, this is 0, this is 0 and this is going to be Y_{21}. So, all the parameters have to go to 0. That means Y_i or Y_{11} is 0 this is also called as Y_{21} or Y_f. Y_{11} or Y_i is 0 that means input impedance should be high, this is high and very close to infinity. The output admittance should be 0 or output impedance should be very high, this is so. Obviously, now if we are going to proceed towards design we will maximize this as much as possible. That is why this alpha effort in boosting up the Y_{21} by having alpha is also done here.

If you want it make it go towards further ideality in the synthesis what should you do? Instead of current mirror of this type we should go for better current mirrors either Wilson current mirror or cascode type of structure so that output impedance is going to be boosted up further. So you can replace these current mirrors by all the modified current mirrors that we have learnt. It will become a better operational transconductance amplifier. So draw the structure of that particular improved operational transconductance amplifier and see how the structure looks. Evaluate the various parameters associated in terms of the operation that is MOS parameters.

This idea is pretty simple because people were habituated to understanding only operational voltage amplifier better than this; this was not being so sought after even though it was being readily available along with 741 and other op amps. And the advantage of this being the frequency compensation in this case is pretty simple because this is high impedance point, I can connect the output capacitor itself as the compensating capacitor which was not possible in the case of operational voltage amplifier because output impedance was low and time constant would have become very low. Whereas we wanted a dominant time constant to come into a picture in frequency compensating.

In this particular case therefore this structure has a very easy frequency compensation procedure that you can simply use the output capacitor itself or put an output capacitor here in order to make the circuit become stable at the required application. This is a major advantage of this. Other than this obviously if you want to use it the load resistance is going to be appearing here and therefore the voltage gain will be simply 2 alpha gm times R_l.

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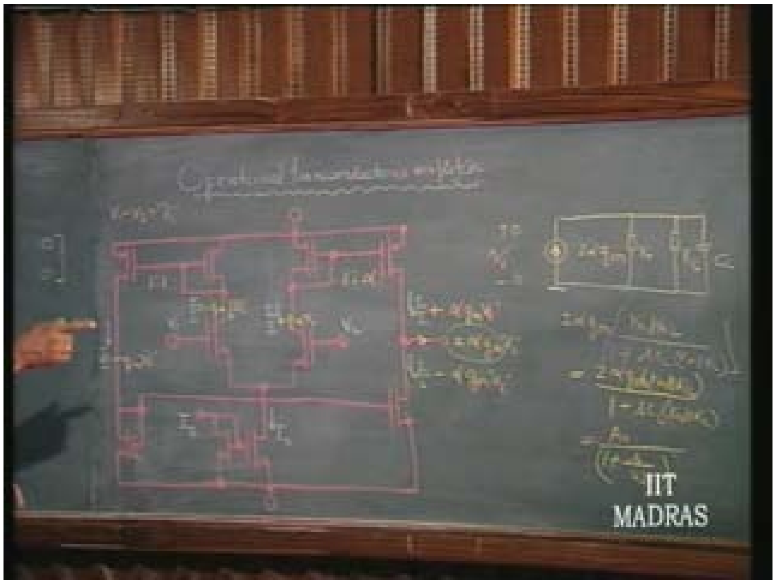

You can see that the equivalent circuit will be a current source with 2 alpha gm if I put it this way, I can put it either way, this is the V_i grounded and then the output impedance of the transconductance amplifier which is pretty high which you can evaluate and then the load if any you are putting and the capacitor that you might be putting.

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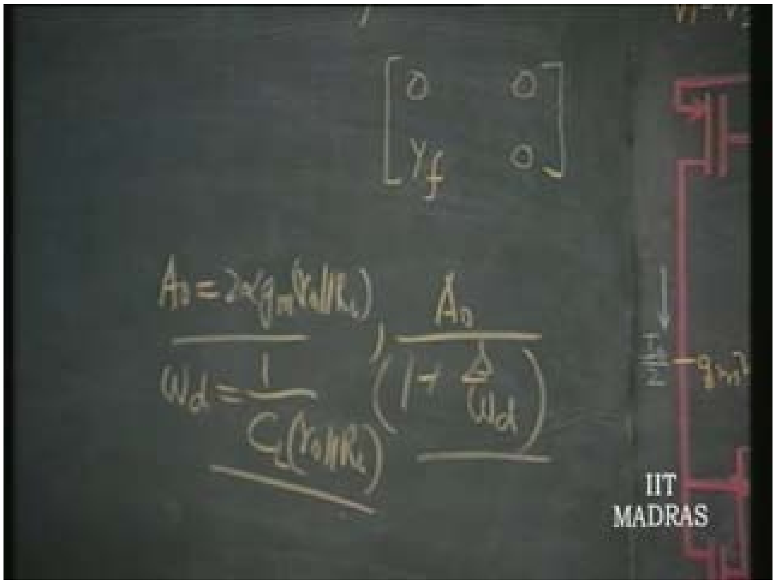

The voltage that is going to be developed is going to be 2 alpha gm into r_0 parallel R_l by 1 plus SC_l into r_0 parallel which can be treated as twice alpha gm r_0 parallel R_l is nothing but A_0 and 1 plus s by the omega dominant here is going to be 1 by C_l into r_0 parallel R_l. So, this is the nature of gain variation of this operational transconductance amplifier which is frequency compensated already. Now A_0 by 1 plus s by omega d where A_0 is going to be twice alpha gm r_0 parallel R_l and omega d is going to be 1 by Clr_0 these are the parameters of importance.

Now, after this the use of this is going to be similar to the operational amplifier voltage amplifier that we are accustomed to using and there is no difference. However, since this does not contain any resistor internally and you can apply a current biasing here through the external resistance we can pump in a current here and this current can be varied and gm is going to depend upon current. Therefore you change the gain as well as the bandwidth using this current of this structure.

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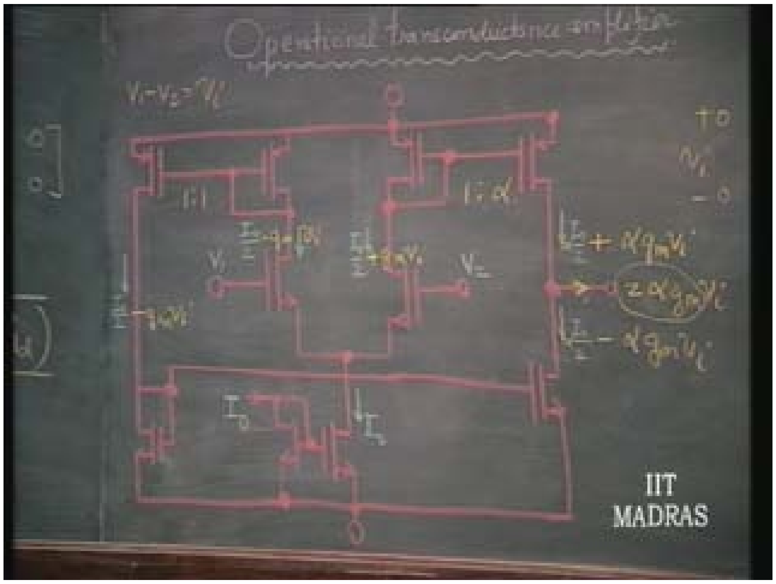

So I_0 can be used to change the gain of this structure so it becomes a current controlled operational transconductance amplifier. The conductance part can be current controlled. This is one of the uses of the transconductance amplifiers. The gain of this becomes current controlled, that current can be obtained by another voltage. If that is the case it is a candidate for, I have output equal to input times the gain. The gain in turn is current controlled which can be made another voltage control. It is also a multiplier. This is something we can specially use it for straight away.

Gain controlled amplifiers can be used for operation of multiplication or modulation or demodulation etc. That is one advantage of this transconductance type amplifier. Originally it was primarily being used here. We have now seen two of the most useful types of operational amplifiers. There are two other types which not so popular yet. Some of the important applications of these operational amplifiers were responsible for ICs to emerge with these as building blocks. Let us discuss how these operational amplifiers are used in other ICs which are also coming out as SSIs or MSIs for multiple usages that are repeated usage as building blocks. So in that context we would first start with the most important application of operational amplifier ever that is instrumentation amplifier IC, the IC instrumentation amplifier.

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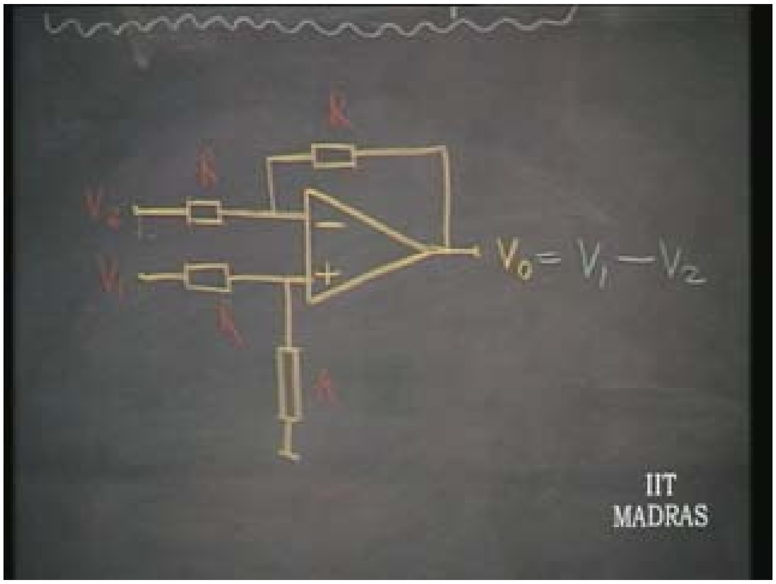

As I mentioned, even though voltage regulator is a very trivial application of the differential amplifier or feedback amplifier it is used to the maximum extent. The demand for such an IC is the highest ever. Similarly, instrumentation amplifier obviously the name suggests is the first amplifier stage for any instrumentation application where you are sensing the signal from the sensor and now you would like to amplify it sufficiently. This is basically the pre amplifier stage. It has lot of responsibilities and its use is prevalent in almost every instrumentation system block.

Therefore, we have to thoroughly know about what additional features the instrumentation amplifier must have, and how to build such instrumentation amplifiers using these active blocks as we are now trying to explain, for example transconductance type of amplifier or voltage amplifier etc. Any one of these blocks can be used to build an instrumentation amplifier.

Let us see how we can build this using operational voltage amplifier. Since voltage amplifier came into existence first let us see how this configuration is going to be synthesized. Instrumentation normally involves a measurement of pressure, force, weight etc where in let us say a strain gauge bridge is used to convert this pressure, force or weight into a corresponding change in resistance in a bridge. So this has to be amplified, this signal that is obtained is going to be of a very small level and this has to be amplified.

Obviously a bridge measurement means it is a differential measurement of voltage. Then we would like to use straight away a feedback configuration. This is called as the difference amplifier using an op amp. For example, these are all equal resistors then obviously V_0 is going to be equal to, we can show that if this is V_1 V_2 then this is equal to V_1 if you just check this, you can apply superposition theorem, V_1 is going to appear here as V_1 by 2, this is grounded so this is nothing but an amplifier of gain 2 so 2 into 1 by 2 so V_1 is going to appear as V_1.

On the other hand, when you ground V_2 this is going to appear as minus V_2. This clearly is something that will determine V_1 minus V_2 the difference in the two voltages and that is why it is called the difference amplifier. If I am using an ideal operational amplifier it is having what is called as differential gain is equal to 1 because differential signal is V_1 minus V_2, common mode gain is 0 because if I make V_1 is equal to V_2 output has to be 0. Ideally speaking this particular difference amplifier has a CMRR which is infinity. But what is not borne in mind is the fact that these resistors cannot made exactly equal in spite of the fact that you might have a very good operational amplifier with infinite CMRR.

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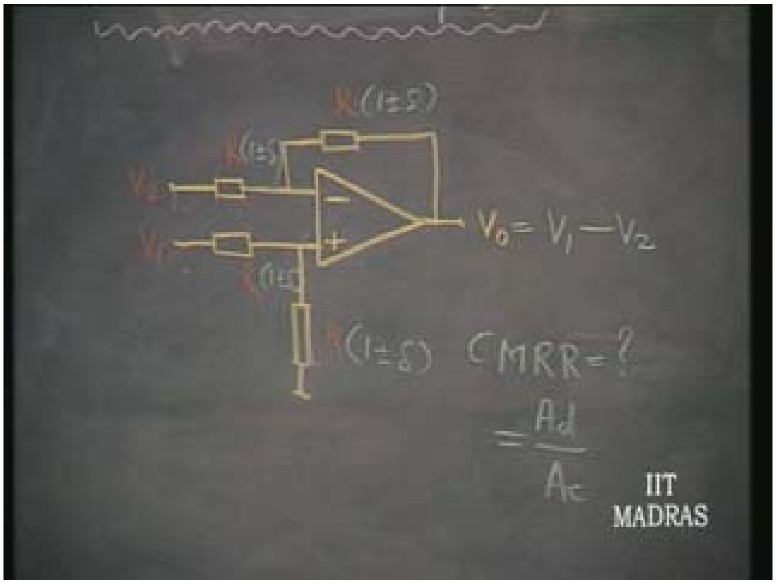

If these resistors are having certain tolerance, let us call this as 1 plus or minus delta, 1 plus or minus delta that means the resistance have a tolerance of delta then obviously this CMRR of this structure is not going to be having any infinite value, it is going to be finite. Therefore we should know, in a design of such a structure what the CMRR of this structure is going to be.

CMRR is Common Mode Rejection Ratio which is nothing but differential mode gain divided by common mode gain. Let us purely apply differential mode gain voltage that is V_t by 2 and minus V_t by 2 and check V_t.

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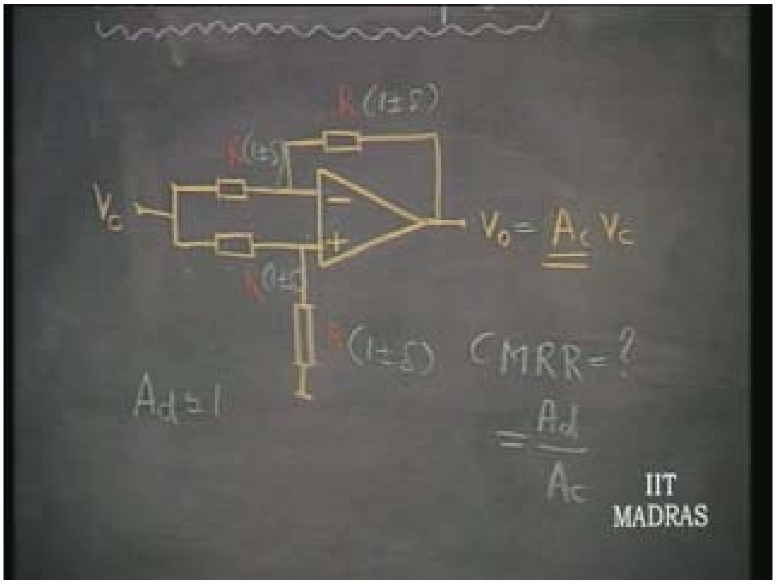

That is going to be resulting in Ad which is very nearly equal to 1 in any case. So Ad is equal to 1. I am saying very nearly equal to 1 because there is a tolerance of delta associated with it, and there will be some variation which we need not bother about. But what matters now is that when V_1 is equal to V_2 what is the output voltage? That corresponds to an output which is A_c times V_c.

So what is this value of A_c? If you evaluate this value of A_c, how do you evaluate it?
You can actually now compute the gain. Under the situation this is R into 1 plus or minus delta, this is also there. So the voltage here is not going to be V_c by 2 any longer. Nominally it will be V_c by 2 but it can deviate from V_c by 2 by an extent of, if this is R into 1 plus delta you have to consider here R into 1 minus delta or if this is R into 1 minus delta you have to consider here R into 1 plus delta the worst case situation.

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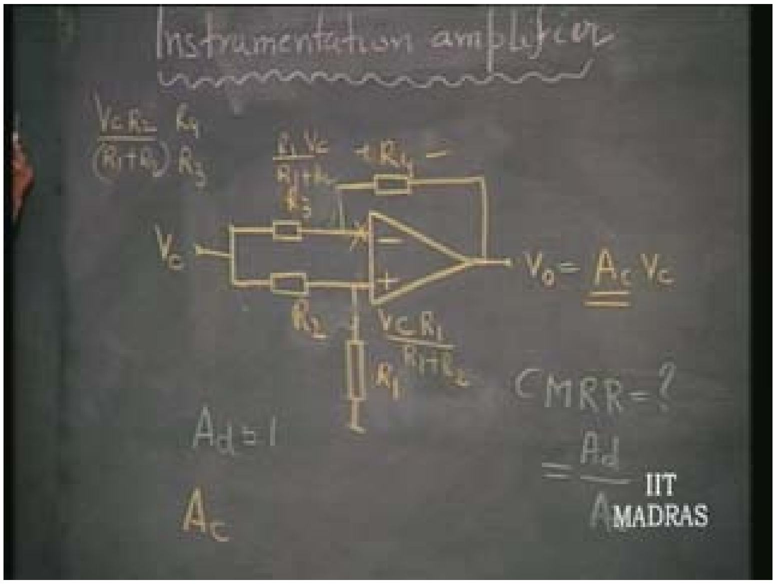

So, in any case it is going to deviate from 1 by 2 by an extent of 2 delta. So, instead of that I will rather put it in a different manner. Assume all these to be different values of resistors R_1, R_2, R_3, R_4 and now you can arrive at the gain.

What will be the gain?
This is V_c, this going to be V_c into R_1 by R_1 plus R_2, this voltage is same as that so this voltage is V_c into R_1 by R_1 plus R_2. Therefore the current in this is V_c minus this which is V_c into R_2 by R_1 plus R_2 by R_3 and the current same current is going to flow through R4 so develop a voltage which is R_4.

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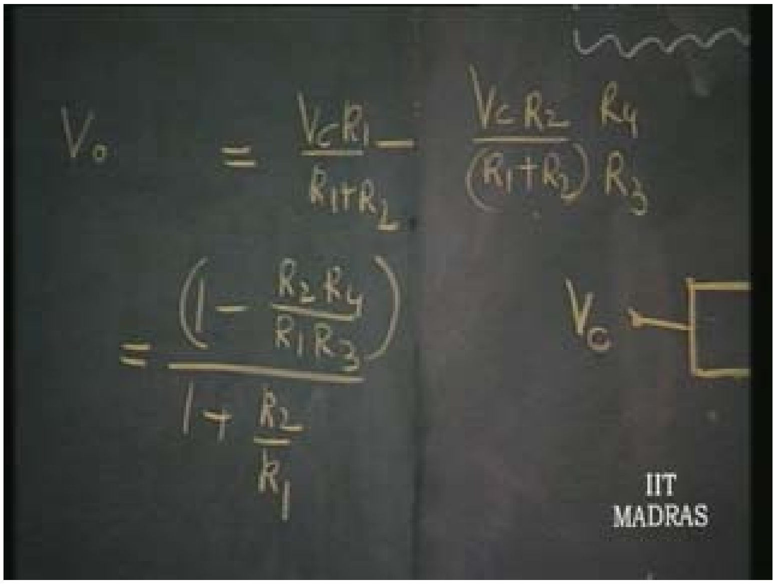

So this is the voltage across R_4 and original voltage was V_c into R_1 by R_1 plus R_2 and that minus this is nothing but the output voltage. So here you can take R_1 by R_1 plus R_2 out which is 1 plus R_2 by R_1 and this one will be 1 minus R_2 R_4 by R_1 R_3.

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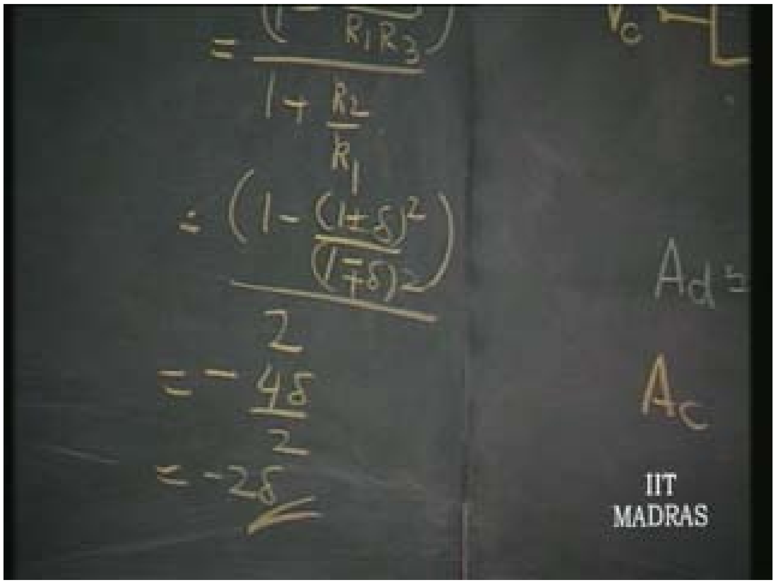

That is, in general the common mode gain of any such difference amplifier. So now you substitute all these values which we have earlier mentioned 1 minus R R R R nominal values gets cancelled and it will become 1. But instead of this you have 1 plus or minus delta square by 1 minus or plus delta square. The lower denominator is going to be 1 plus R R giving you 1 that means 2 plus some delta which we are ignoring compared to 2. But here we cannot ignore this compared to 1 because it is coming as a difference.

Here you can apply the binomial theorem so this factor is going to be 1 plus 2 delta, this will be 1 minus 2 delta, and 1 plus 2 delta by 1 minus 2 delta is 1 plus 4 delta so 1 1 gets cancelled so you get minus 4 delta by 2 or 2 delta. This is an important relationship which you should remember throughout. As a design engineer you should be quickly able to tell what kind of tolerance of resistive components you must select in order to get good common mode gain close to 0.

Now just see if you use 1% tolerance component what happens here? This is 1% that means 1 by 100 then common mode gain is simply 1 by 50 and CMRR of this structure is simply 50 which is grossly inadequate for most of the instrumentation application. Therefore 1% component 1% resistor is called a precision resistor. So, in spite of using precision resistor you are not achieving any good performance from this instrumentation amplifier. This is the mistake committed by most of the instrumentation amplifier design engineers. They ignore the fact that the tolerance of these components become very important in design of instrumentation amplifier. Actually if the tolerance is poor you are not actually amplifying your difference signal in an efficient manner. Apart from the difference signal you are amplifying the common mode signal also and the common mode output is coming as the error term.

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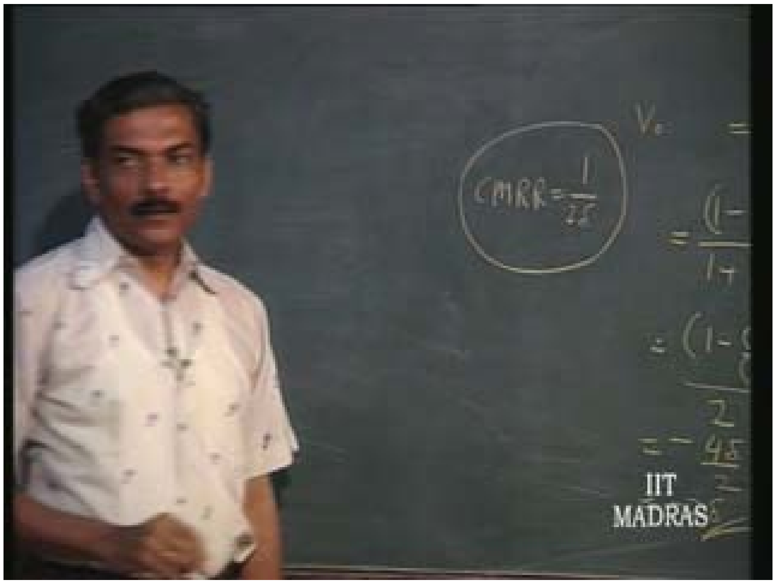

So this kind of design now tells you that this difference amplifier is basically no good in spite of using a very good operational amplifier. It has a CMRR which is 1 by 2 delta. How does one improve this without really getting involved with a very precision component which are not really available in an integrated circuit?

All these components should be within the IC. That means there the tolerance is not still good. Externally if you are making a discrete component version you may select .1% resistors etc easily. But this is not the case in integrated circuit manufacture. For making the fabrication very easy you do not want to trim any component. Therefore you would like to obtain the structure with the tolerance of components available in the technology. If such is the case you cannot make any good instrumentation amplifier using the present day technology as such.

How to get over this problem?

That is, when the circuit designer comes into picture again, the device man says; this is it, the tolerance is this, I cannot give you better tolerance. But still we would like to design instrumentation amplifiers with better CMRR than this. So the circuit engineer now comes to the rescue of this system design.

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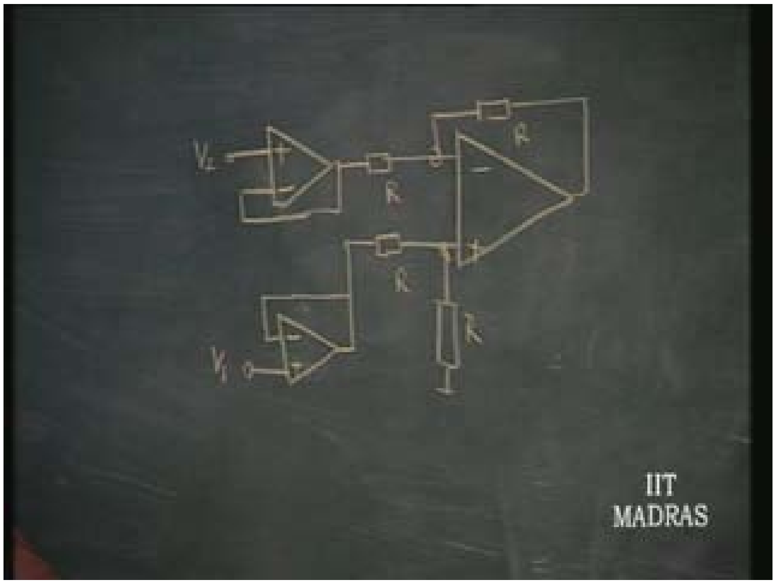

Let us once again consider the same structure. We will use the same structure but we will attach onto this something here R, R, R, R with tolerance equal to delta. Now, obviously this is not the only property of the instrumentation amplifier that is important. CMRR has to be very good for any input stage like in the case of an oscilloscope for example. At the oscilloscope input terminal also if it is a differential kind of measurement the CMRR of the input stage amplifier should be excellent at all frequencies under which you are going to use the oscilloscope. So that part of the circuit takes the most of the effort of a design engineer. This is going to load the bridge, if it loads the bridge again it is going to cause disturbance of the balance and that should not happen. So, an instrumentation amplifier should not load the bridge. That means there should be a buffer stage. Therefore it is obvious that we can modify this structure by using buffer stages.

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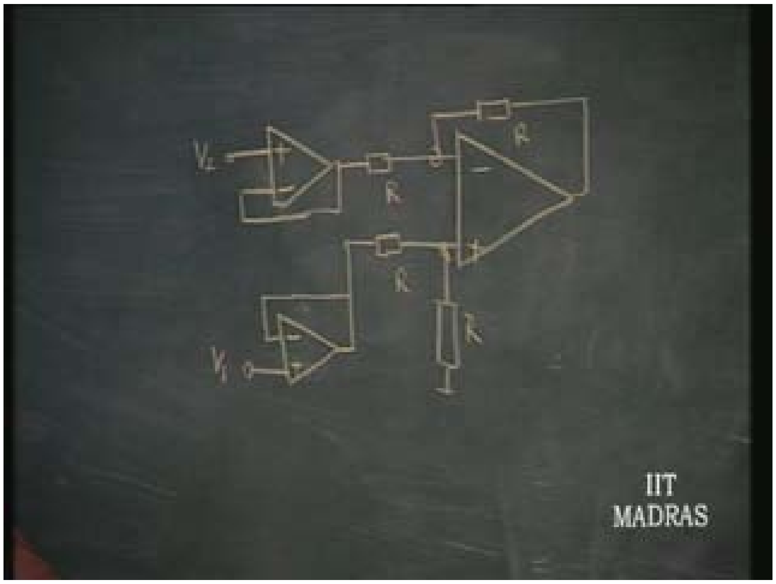

Therefore, instead of applying V_1 and V_2 here we will now apply V_1 and V_2 here. This has not changed anything other than making this difference amplifier not load the bridge and that is taken care of. Otherwise there will be asymmetric kind of thing loading here. Now, if you are using buffer like that you would like to obviously use some gain R_1 R_2 instead of unity gain. Or let us actually put it as R_a and R_b so that it will be different from this.

Now what will be the gain of each of these?
It will be V_2 into 1 plus R_b by R_a and this will be V_1 into 1 plus R_b by R_a.

But what happens to the CMRR of this structure?
The differential mode gain has increased by 1 plus R_b by R_a. But what happens to the CMRR of this structure is that it remains the same as before because both these voltages are individually amplified as 1 plus R_b by Ra. So if you connect these two common voltages V_c that V_c is also going to be amplified by 1 plus R_b by R_a. So the CMRR of this structure has not changed if you just boost up both V_2 and V_1. The problem of this structure comes only because V_2 and V_1 are independently coming into the picture in each of these stages.

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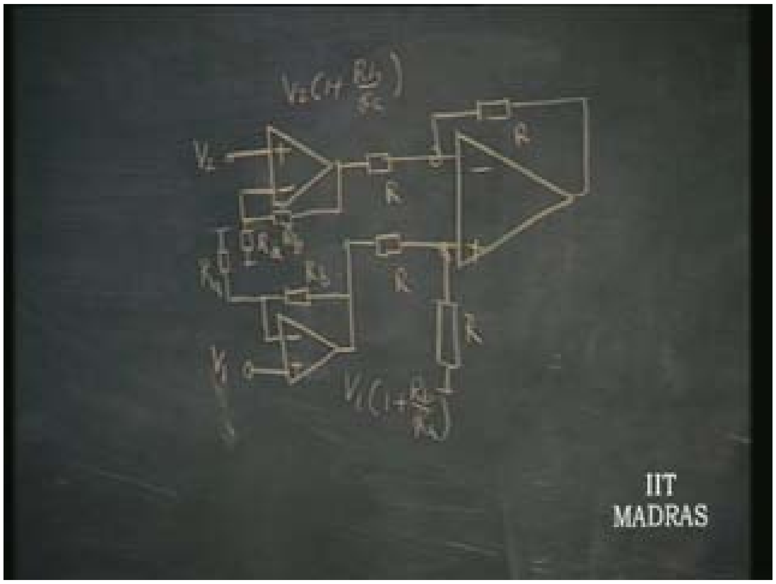

And this voltage is V_1 and this voltage is V_2. The current in this is V_2 by R_a and the current in this is V_1 by R_a. So why not therefore remove this from the ground and connect it together so that the currents become dependent on V_1 and V_2. And the current is going to be not fixed by V_1 or V_2 alone individually but V_1 minus V_2. It is that current that is getting amplified. So if this is V_1 and this is V_2 the current in this is going to be, for example V_2 minus V_1 by R_a.

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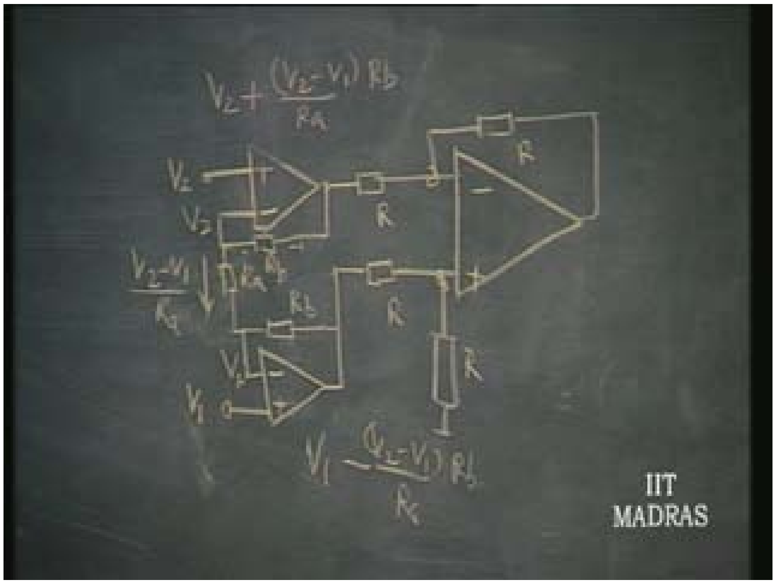

If V_1 is equal to V_2 there is no differential current so if V_1 is equal to V_2 no current occurs here, that is good because when there is common mode voltage there is no current flowing in this resistor. That means this voltage is going to be exactly same as this voltage, this voltage is going to be exactly same as this voltage V_c V_c both are going to be the same. That means this structure is not amplifying the common mode voltage at all. It is simply because I am now lifting it off the ground and connecting it to the other point therefore it is only amplifying differential signal. This is one of the most useful three instrumentation amplifier used almost universally in most of the applications. Therefore you can see here that the output voltage is going to be V_2 plus V_2 minus V_1 by R_a into R_b that is the drop across this.

Now what is the voltage here?
This is V_1 minus V_2 minus V_1 by R_a into R_b. That means you can now make R_a as small as you please and get it to amplify only the differential mode signal V_2 minus V_1. The common mode signal still remains V_c, V_2 plus V_1. This voltage plus this voltage divided by 2 is the common voltage remains the same as before. So the common mode gain of this additional structure is 1 whereas its differential mode gain is this minus this so V_2 minus V_1 plus V_2 minus V_1 into R_b by R_a. Or its differential mode gain is 1 plus R_b by R_a.

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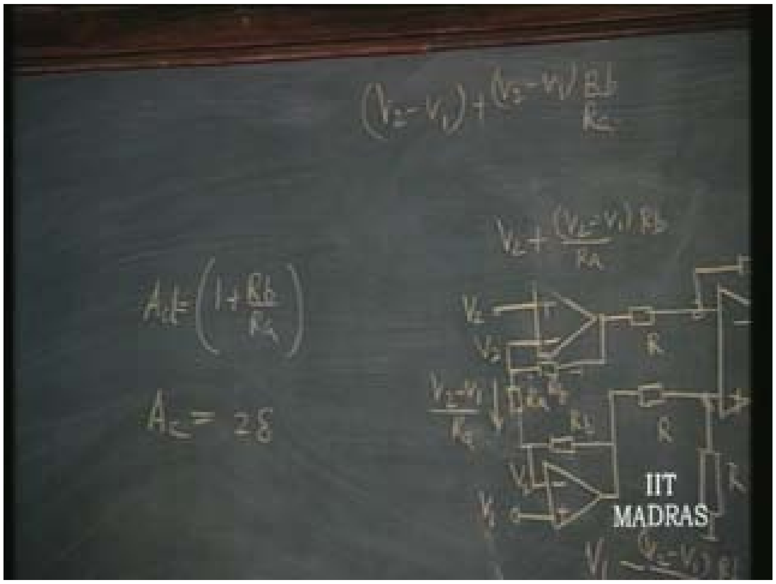

This differential mode gain is going to be 1 plus R_b by R_a and the differential mode gain of the entire structure is 1 plus R_b by R_a because this differential amplifier has differential mode gain of 1. And the common mode gain of the entire structure is going to be 2 delta so the CMRR of this entire structure is independent of the tolerance of R_b by R_a. Therefore R_b by R_a has the normal effect. That means if there is a 10% variation there is going to be 10% variation in the gain that is going to be normal. These Rbs if they are different then there is going to small difference. That difference is going to get added on to a huge value of V_c itself which is going to be V_c into R_b 1 minus R_b 2 by R_a.

So even though it is going to be boosted up it is going to be boosted up to a minor extent. So, common mode gain is very nearly equal to 1 itself even if there is difference in these two R_bs to a certain extent 10%. Therefore, because there is a common mode voltage V_c, to that you are going to add R_b 1 minus R_b 2 by Ra so it is not going to matter whereas the differential mode gain is going to be totally determined by R_b by R_a. The R_a tolerance does not come into picture at all in the differential mode gain. So R_a can now independently vary, this is another fact. You can vary it by just varying that value and you get a variable gain in the instrumentation amplifier. So now obviously the CMRR can be made pretty high by making R_b by R_a pretty high. Therefore, in spite of using poor tolerance resistive component within the IC we can achieve reasonable value for the CMMR for the instrumentation amplifier if we are prepared to go in for this three amplifier structure.

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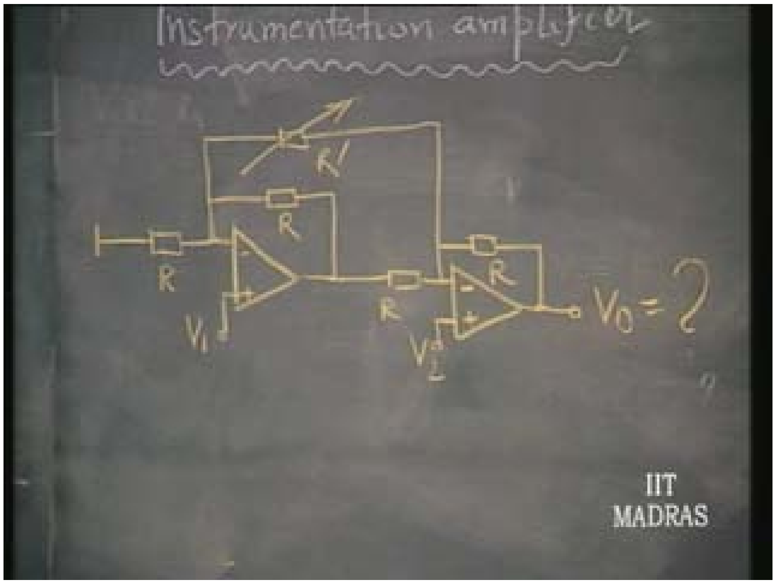

There are some minor variations about instrumentation amplifier. You can obtain an instrumentation amplifier using two op amps also. That configuration has not become popular primarily because it is not symmetric. The signal handling ability of the op amps will differ. Whereas here signal handling ability will be the same, requires being the same because common mode voltage appears here whereas here different values of voltages will come at this point. So the large signal property is going to be different, it is not a popular one. But this is a possible configuration.

Again all these resistances have to be equal. Show that this instrumentation amplifier also has its gain dependent on R dash and these R_s have to be exactly identical. If there is a tolerance of delta there will be finite value for CMRR. Obtain the CMRR of this structure and the differential mode gain. But this is not really available as an IC. The entire thing is available as an integrated circuit for use.