Electronics for Analog Signal Processing - II
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Lecture - 18
Wideband (Video) Amplifiers

In the last class, I had demonstrated to you that if an amplifier A, amplifier has a gain A, and it is having a single pole, the gain of the amplifier - D C gain - is A naught, and its bandwidth is W d indicating only one pole, dominant pole, exists in its useful range.

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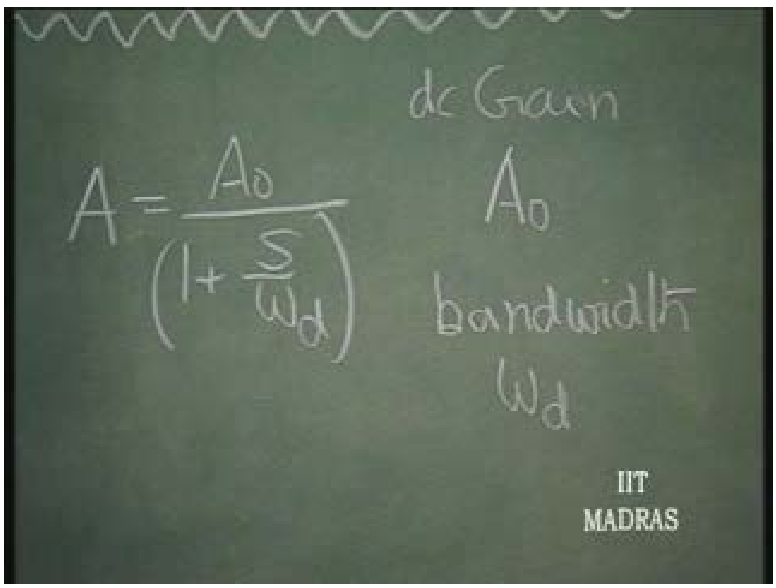

Then we said, a measure of the amplifier performance is defined by what is called gain bandwidth product, which is equal to A naught into W d.

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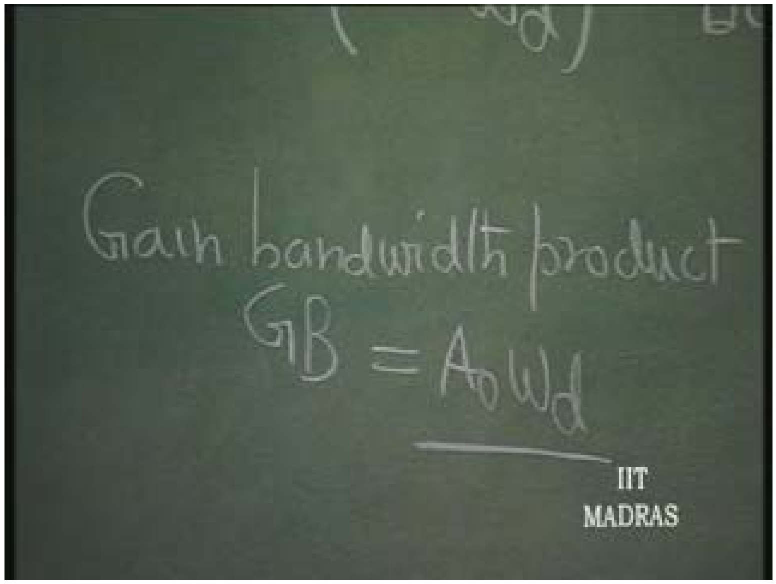

So, this is a very important parameter associated with any amplifier. Gain bandwidth product. Why? Because, if I use this in a negative feedback configuration in order to desensitize the gain with respect to the active parameter A naught and Omega d, then...

Let us say, this is my amplifier with gain A; and I will use it as a negative feedback. One of those configurations which we have been constantly using for demonstration of this; in frequency compensation also was this; R 1 R 2. Beta, let us say, is R 1 by R 1 plus R 2; that is the amount of negative feedback from output V naught; this is the amount of output fed back to the input.

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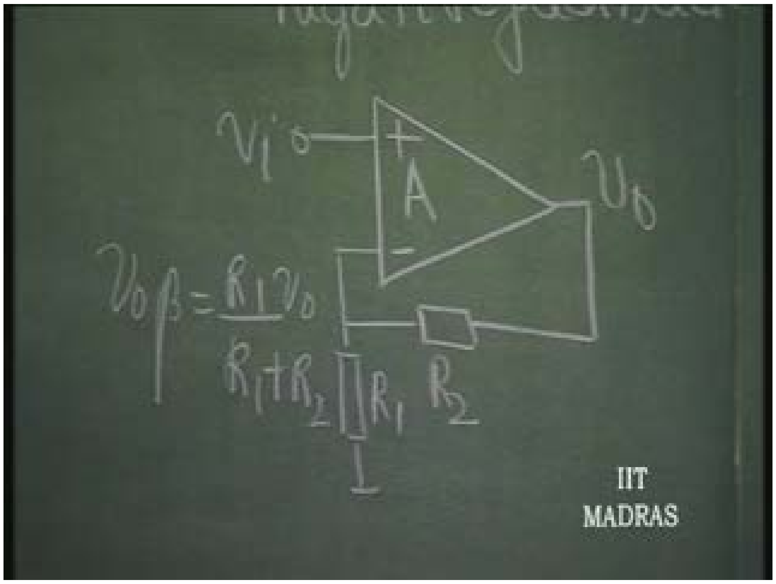

Then we know that the amplifier gain is going to be A divided by 1 plus A Beta. This we have demonstrated earlier; or this is written as V i by Beta, which is the ideal gain under the situation A goes to infinity, divided by 1 plus 1 over A Beta which is A naught Beta 1 plus S Omega d. This we had demonstrated earlier also.

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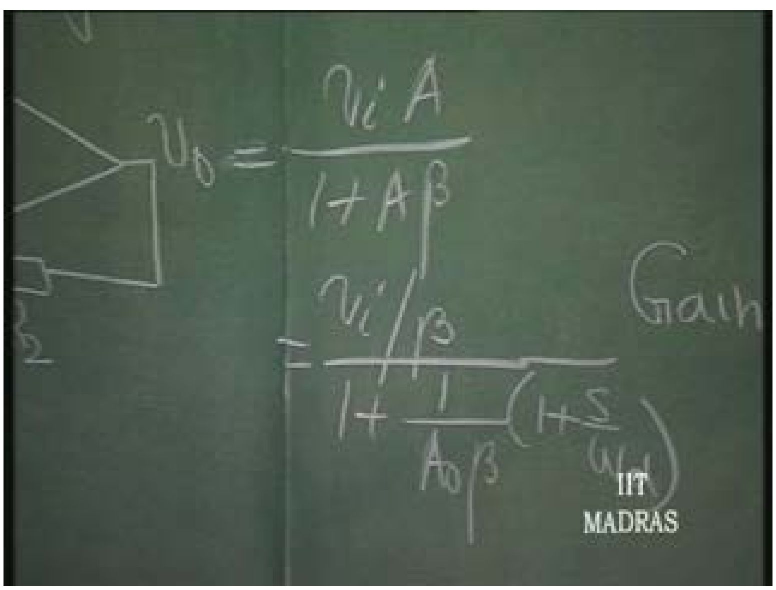

And we see that V naught is equal to V i by Beta divided by 1 plus 1 over A naught Beta which is very small, plus S into Omega d A naught Beta.

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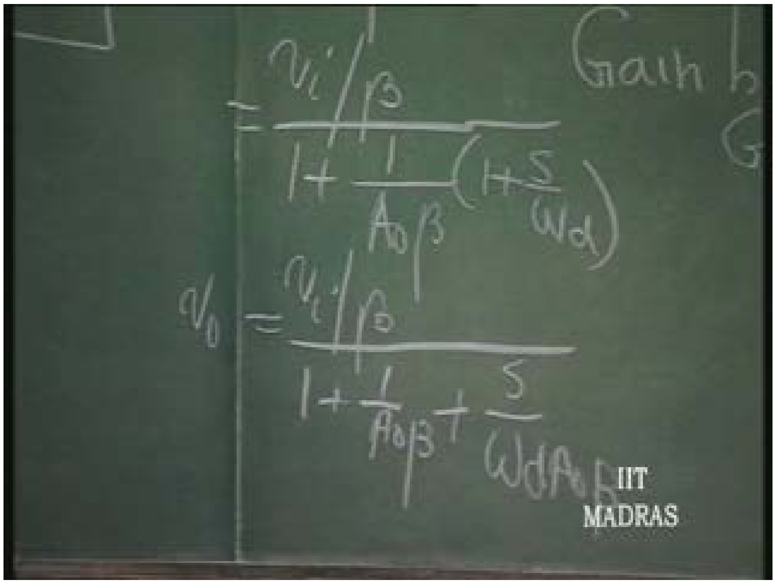

This can be ignored.

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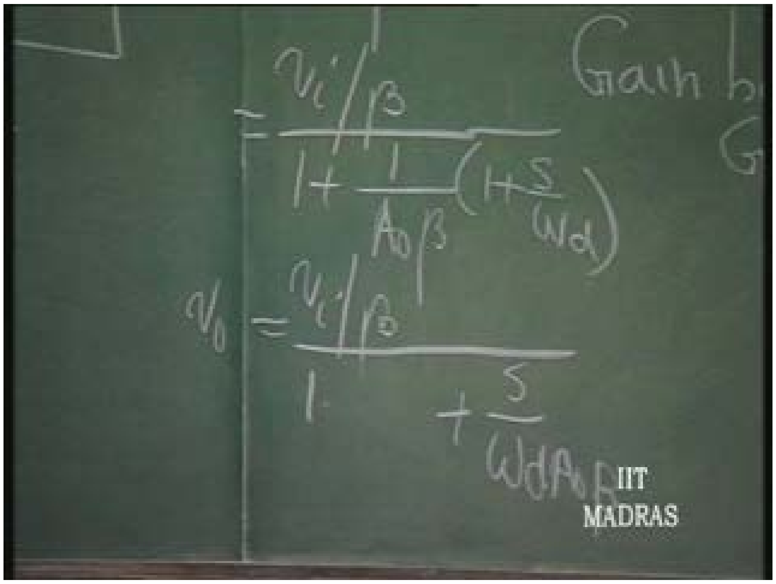

And therefore, for the new amplifier now with negative feedback, the gain, D C gain, is 1 over Beta and bandwidth equals Omega d into A naught into Beta. So, this is an important aspect; the bandwidth of this amplifier after negative feedback has improved by a factor of A naught into Beta.

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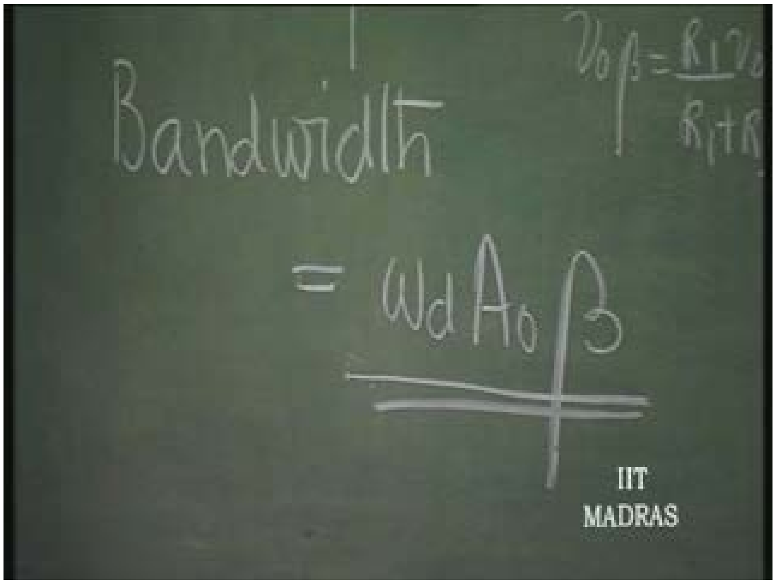

So, let us say, I have designed an amplifier whose gain is sort of 10, using an amplifier whose gain was 100. Let us say A naught was 100; and I am designing an amplifier with a gain of 10. That means Beta is 1 over 10. So then, the bandwidth, let us say is 10 to power 6 radians per second for this. Then the bandwidth for this is going to be, amplifier with gain equal to 10, is going to be equal to, 10 to power 6 into A naught into Beta, which is 10 times the original bandwidth. That means it will be 10 to power 7; the gain is equal to 10.

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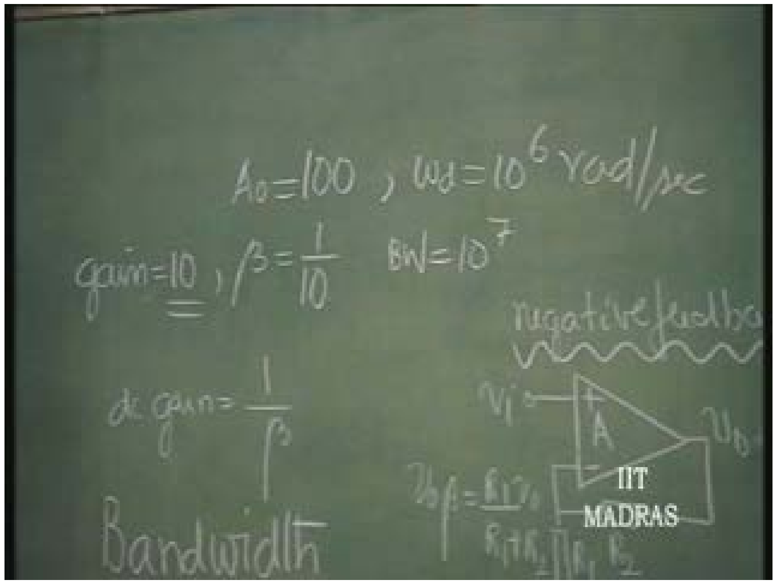

So, this is what is going to happen in wide banding. So, you can always design a wide band amplifier starting from an amplifier with limited bandwidth. You can design an amplifier with wide band and desensitize the gain. Gain is going to be least sensitive to variation in A naught; wide bandwidth using this negative feedback. But, we have a problem with negative feedback.

And I told you, if this becomes...instead of a single pole it becomes a two pole system, then we will have an amplifier with negative feedback whose poles can become complex conjugate pair; and it can start peaking. So, it starts behaving in a odd fashion at higher frequencies. This is one danger. Further, if it becomes three poles, we saw that there is this danger of instability occurring; it may go into oscillation.

So, in order to prevent that from going into oscillation, we could take recourse to frequency compensation making one of the poles dominant. In the process, we are cutting down the bandwidth. So, we were cutting down the bandwidth in order to make it work with negative feedback.

This is where the negative feedback fails to give you the widest possible bandwidth. So, even though after cutting down the bandwidth, then, gain into bandwidth is going to remain constant; and within that gain into bandwidth product you can get wide band amplifiers designed with desensitized gains, etcetera. But, this kind of dominant pole compensation is always going to result in lower gain bandwidth product.

Instead, I said, we can convert that third order system into second order system by using pole zero compensation. So, this kind of compensation, we can sort of demonstrate by giving an example. So, my purpose now is to make this circuit work for the widest bandwidth possible so that I am designing a wide band amplifier using negative feedback. So, what kind of compensation is suited? For that particular gain you require, you must just give enough margin so that it does not oscillate.

So, this is the optimum way of providing compensation so that it works best for the widest possible range of frequencies. So, using an example of wide band amplifier design with negative feedback, I am going to demonstrate this effect.

Let us now understand this principle of wide banding in negative feedback structures by solving this Example 17.

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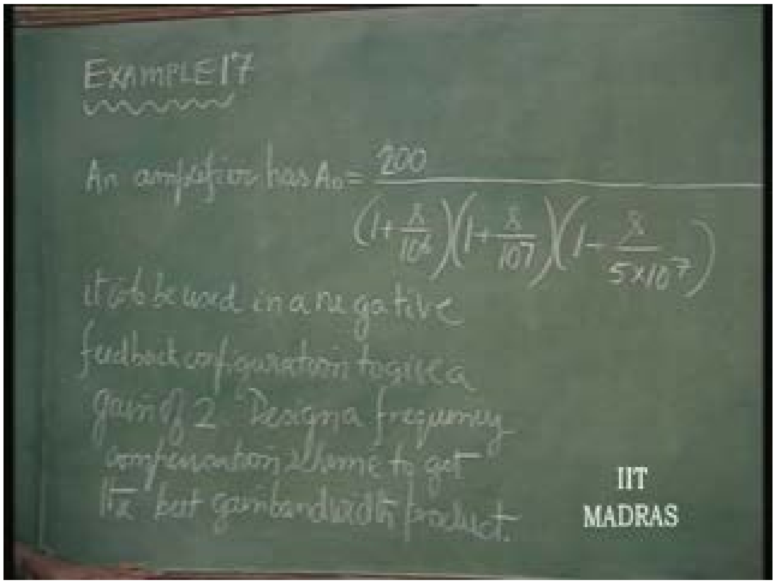

An amplifier has, A naught of this type: 200 divided by 1 plus s by 10 to power 6, plus 1 plus s by 10 to power 7, plus 1 plus s by 5 into 10 to power 7. This kind of pole, three pole.

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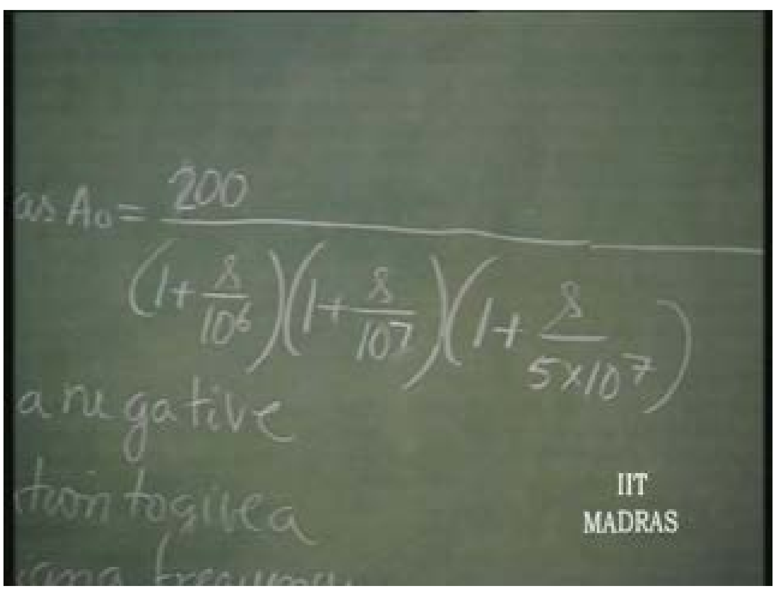

It is to be used in a negative feedback configuration; is to be used in a negative feedback configuration to give a gain of 2.

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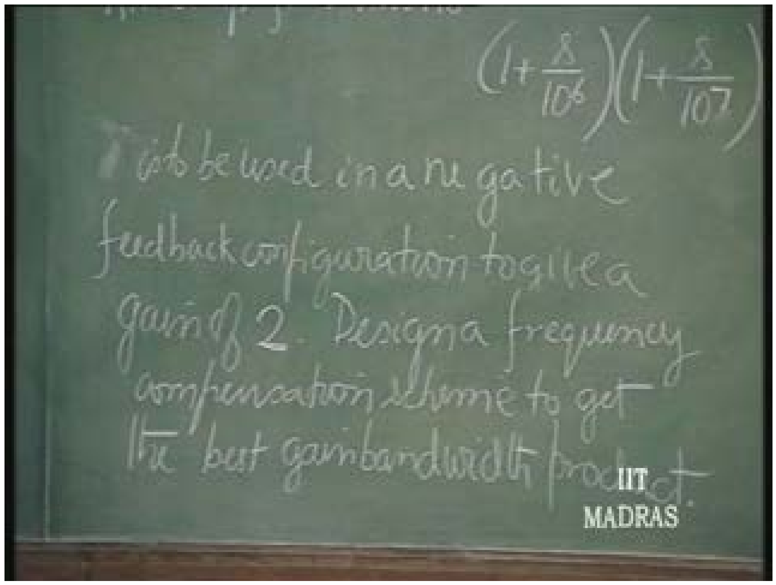

That means this is the amplifier, differential amplifier, let us say, with A of this type and it is to be used to get a gain of 2 which can be done by giving a feedback factor of half; Beta is equal to half. V naught over V i is going to be 1 over Beta. So, that is actually going to be 2 divided by 1 plus something. We want to maximize this bandwidth here. What should we do?

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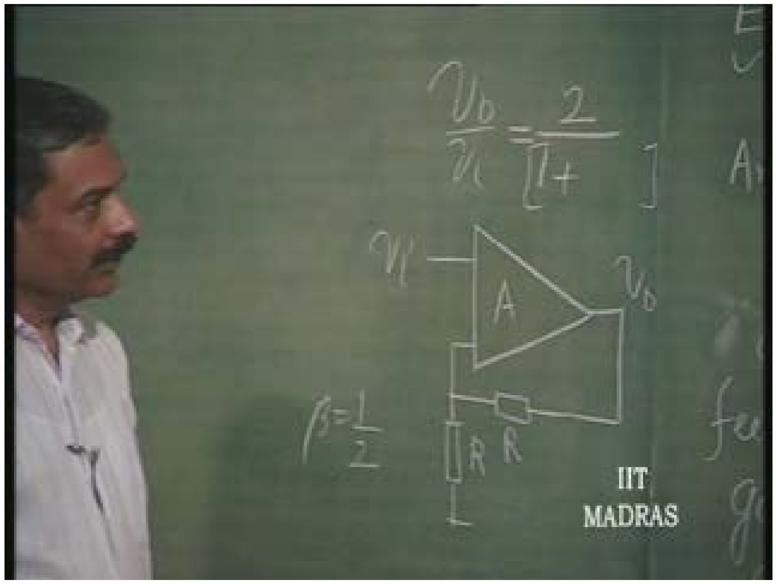

Since, with this three pole... With one pole, it is no problem; with three poles, it might now go into oscillation. Let us examine.

If it is not going to oscillation, please see here; if it is not going to oscillation, then the bandwidth is equal to 10 to power 6. Actually, the gain bandwidth product is 200 into 10 to power 6. That is the best gain bandwidth product for this already; but if it goes into oscillation, one way of compensating is to shift this down so that these become insignificant in the frequency band. So, this is to be brought down. But that way, automatically, you are cutting the gain bandwidth product.

So, in the wide band amplifier design, that is not done. In a general purpose amplifier this is done so that the user can use it any configuration he wants and see no oscillation. So, that is applicable only for low frequency purposes. In a wide band amplifier, this is not done. You would like to retain this as a dominant pole, which means, now we have to cancel the other pole, the next pole, which is influencing this in terms of phase shift so that this becomes dominant.

That means, if this is cancelled, the distance between this and this increases enormously; and another pole is going to be introduced far away so that these two poles do not come into picture, and this is the dominant pole. That is the idea behind wide banding.

So, let us see how practically we can do it. So, given that you cannot meddle with whatever structure the amplifier has, you can only meddle with the feedback structure here. Let us see how it can be introduced in the feedback structure so that there is a pole zero compensation for this. So, we are now discussing about how to do pole zero compensation.

I had discussed earlier itself. Now, we have to make this R and this R; but this R now can be conveniently split, let us say, to R. Let us say Alpha R and 1 minus Alpha times R so that the total is still equal to R. Alpha R and 1 minus Alpha R, so that the total is still equal to R, such that now, I can bring about a zero here conveniently, taking portion of that R. So, I put a capacitance here. Now, for this network let us write down how Beta will look like.

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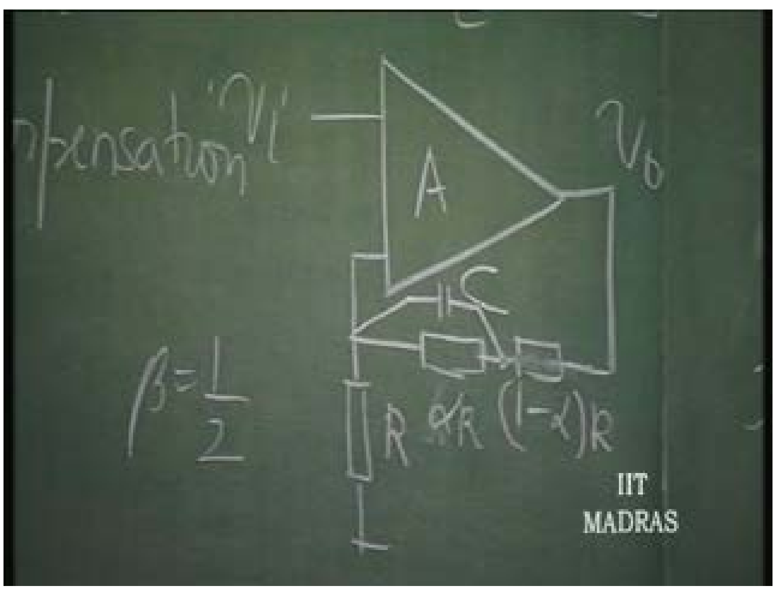

So, actual Beta without this was half. Now it is R divided by 1 minus Alpha times R plus this resistance, plus Alpha R divided by 1 plus s c into Alpha R. This is the attenuation, Beta. Now, Beta has been made frequency dependent; so, it can give you the half at low frequencies as well as result in a zero at a convenient point to cancel one of the poles and make a pole located farther away.

So, let us see whether it is done. So here, you take out this R into 1 plus s c Alpha R; comes to the numerator. So, you get 1 minus Alpha R plus s c Alpha R into 1 minus Alpha times R, plus Alpha R.

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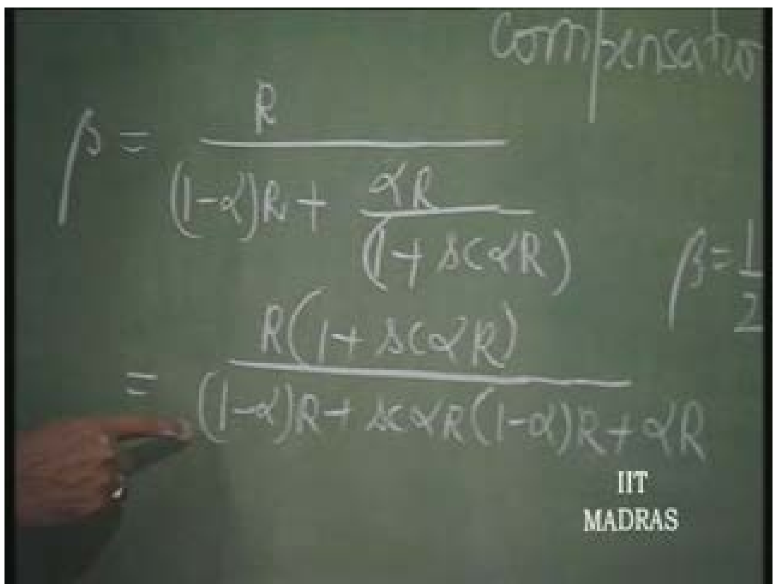

So, this Alpha R plus 1 minus Alpha R give you R; 1 minus Alpha R plus 1 minus... plus R, R plus 1 minus Alpha R plus Alpha R by 1 plus s c Alpha R. So, you get here 2 R. I did write this.

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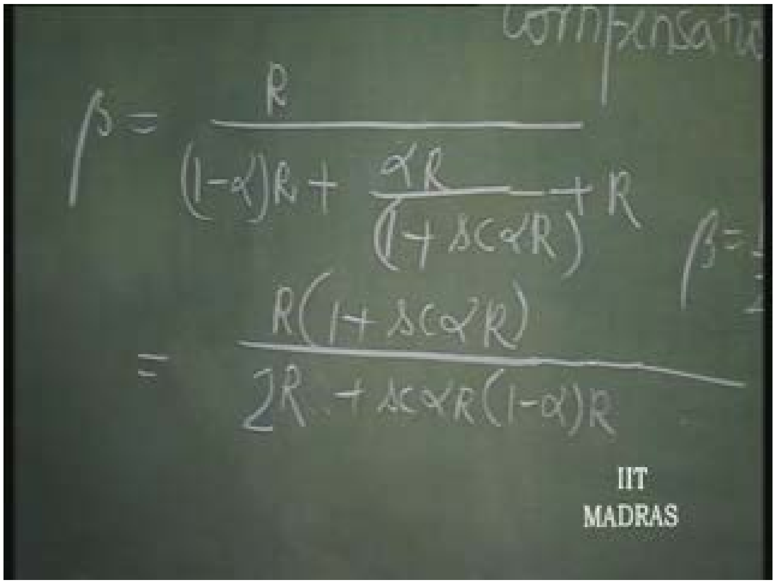

So, this can be rewritten as... take out this 2 R; so you get half, which is what you wanted. 2 R out. This will be 1 plus Alpha s c R divided by 1 plus... R has been taken out; Alpha into 1 minus Alpha s c R.

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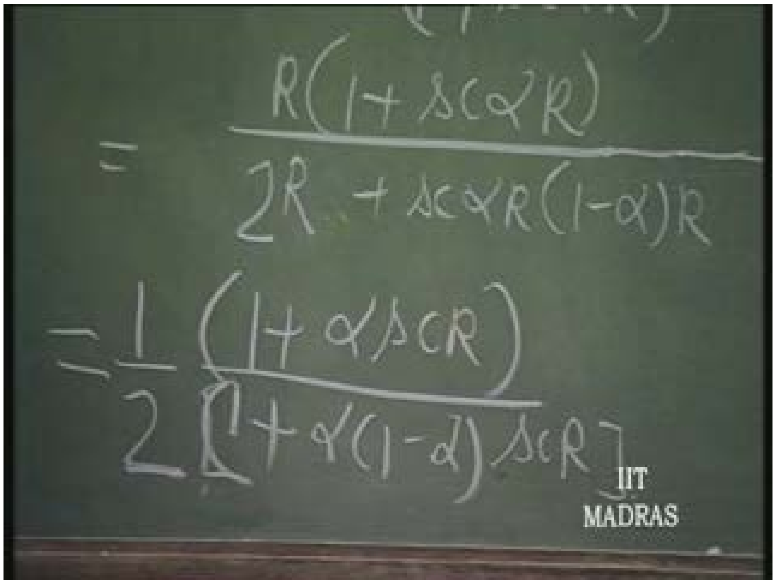

So, as far as this is concerned, we have the zero located Omega z at 1 over Alpha C R, 1 over Alpha C R, and the new pole located at 1 over Alpha C R, which is zero, into 1 minus Alpha. Look at that.

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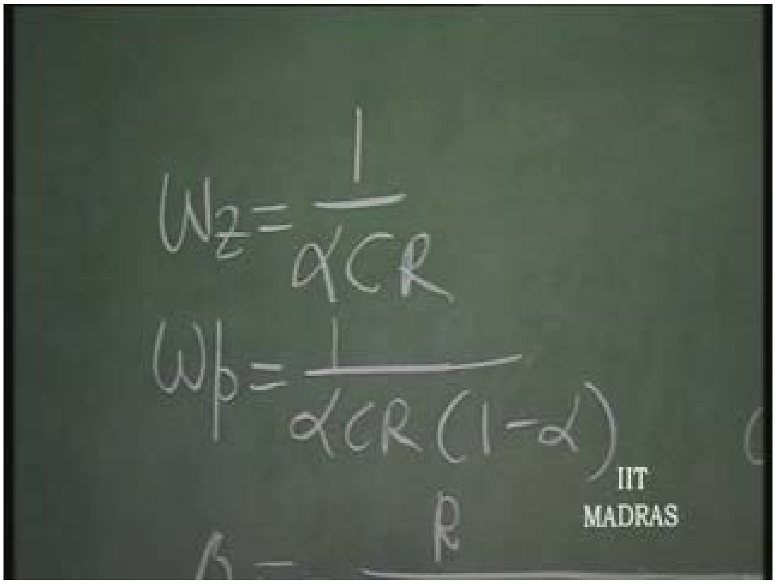

That means we have zero located at whatever we want. That can be located conveniently by selecting Alpha C R and then the pole is located at Omega z divided by 1 minus Alpha. So, by making Alpha close to, let us say, Alpha is let us say close to 1, this is actually equal to pole.

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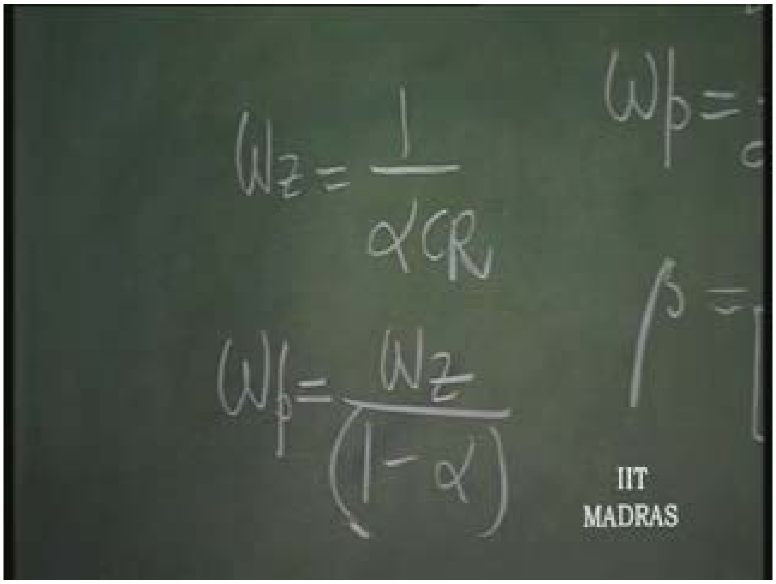

The pole is going to be located farther away from the zero. Alpha, if it is close to 1, let us demonstrate this. Alpha is equal to, let us say, 1 over 19. I am just going to take it as a demonstration. Omega z is going to be 19 divided by C R; Alpha equal to 1 over 19; sorry, 18 over 19. Alpha equal to 18 over ...; close to 1.

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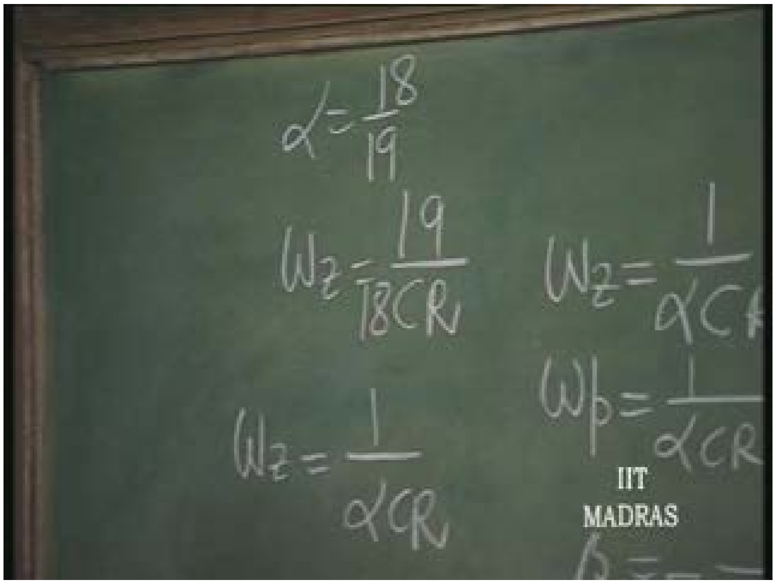

So, you get here this as Omega z divided by 1 minus 18 over 19; which means this is equal to 19 minus 18, 1. So, 19 times Omega z.

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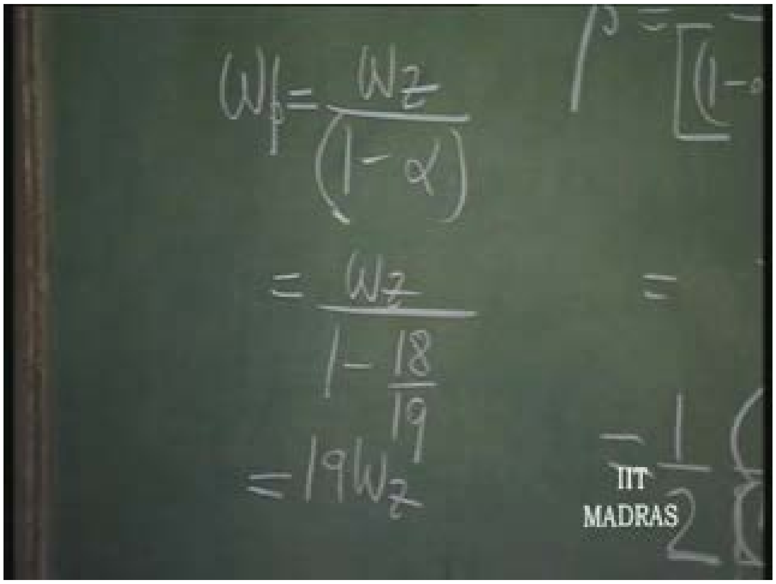

So, this is nearly 1 over C R; whereas this is 19 times that Omega z. So, if you select, for example, this as let us say, 19 by 20 for example, this will be 19 by 20, which is very nearly 1 again.

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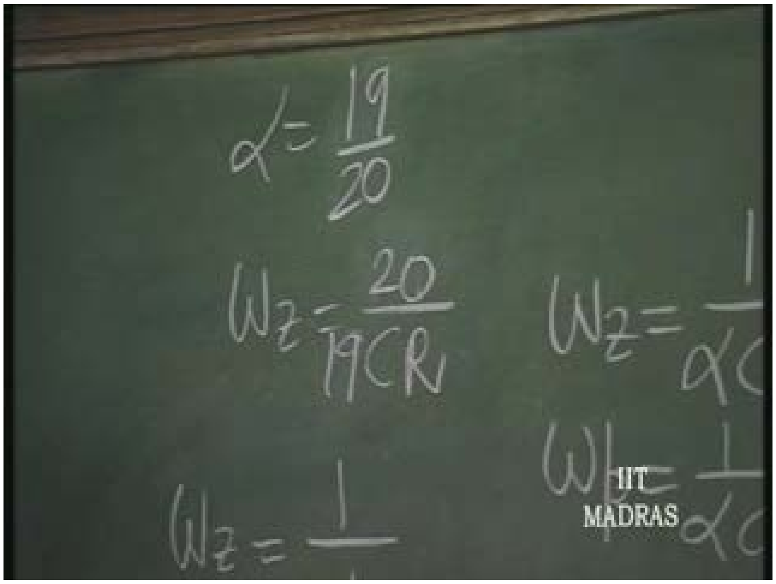

And this will be 19 by 20. This will be at 20 times Omega z. So, just we can therefore, by selecting Alpha close to 1, make the pole go farther and farther away.

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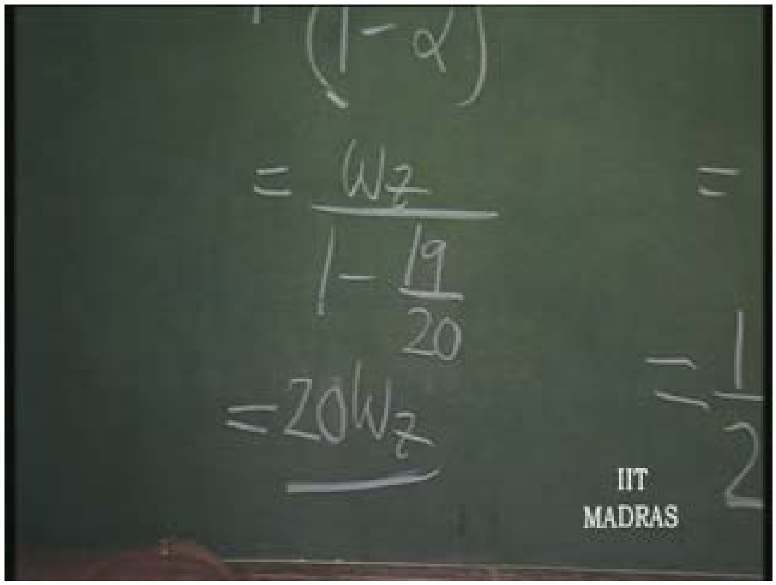

So, let us for argument sake, leave it at this. That we are going to select Alpha as 19 by 20. So, that might be sufficient. Let us examine. If it is not sufficient, we will select Alpha further close to 1. So, Alpha has been selected as 19 by 20. Then Omega z is 20 by 19 times C R which is very close to 1 by C R; that has to be made equal to, let us say, 10 to power 7. I will make this to equal to 10 to power 7.

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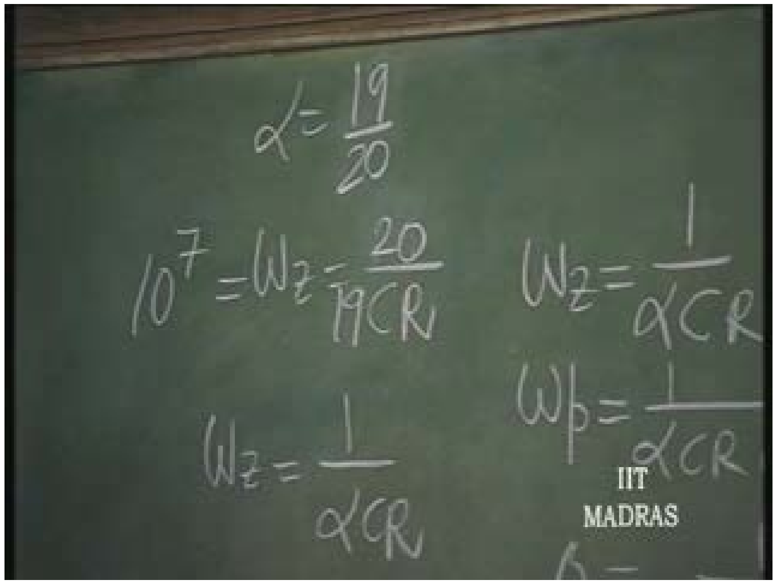

So, I am now introducing in this a Beta which is half. Beta is going to be half. So, in my problem I will redraw this here. 200 into half; this half, into 1 plus s into 10 to power 7. That divided by... sorry. s by 10 to power 7. This divided by s by 10 to power 6, 1 plus s by 10 to power 7, 1 plus s by 5 into 10 to power 7. And, where does it introduce this pole? It is going to be at 20 times Omega z. So, 1 plus s by 20 times 10 to power 7. So, is that clear?

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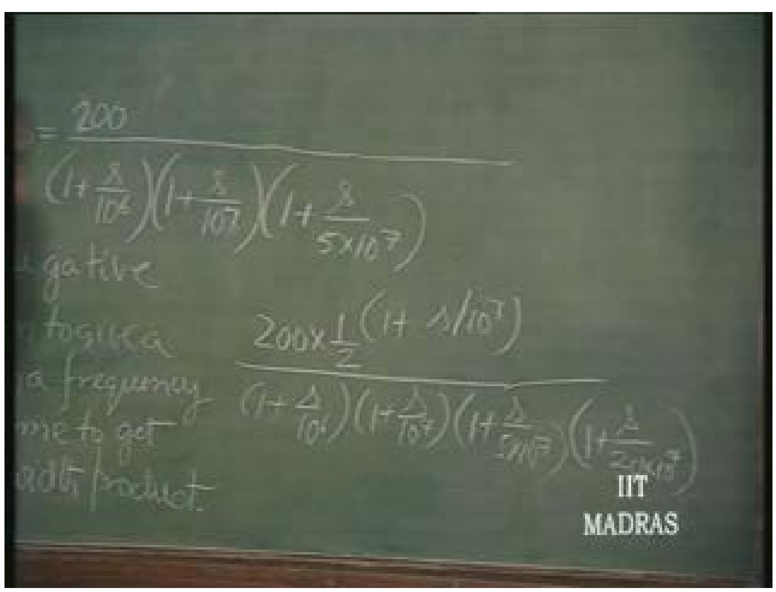

Now, this gets cancelled with this and this becomes 100.

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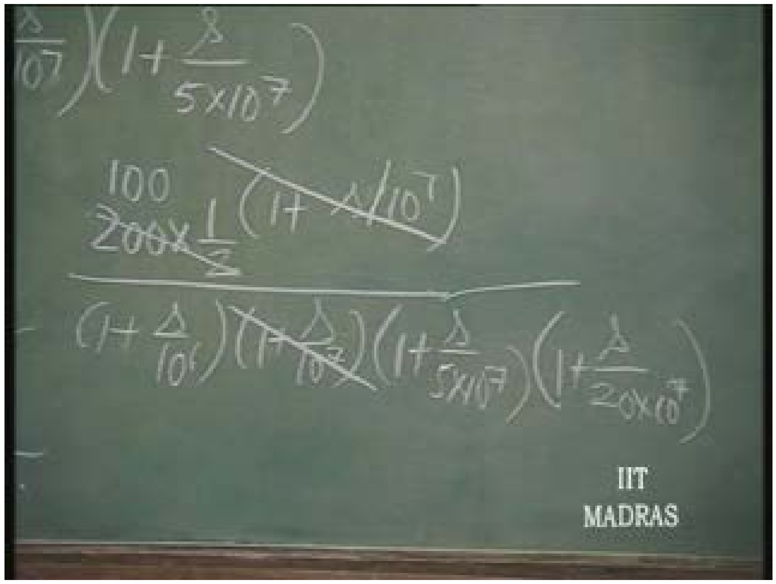

So, we saw that A Beta now gets modified as 100; same as value as before. This remains the same. Now, the second pole has got shifted from 10 to power 7 to 5 into 10 to power 7; and a third pole has been introduced at s by 20 into 10 to power 7. So, this is the new modified a b where this 1... This is 10 to power 6. Thank you. So, first pole remains at 10 to power 6; second pole has got shifted from 10 to power 7 to 5 into 10 to power 7; and the third pole is 20 into 10 to power 7. This has been reintroduced.

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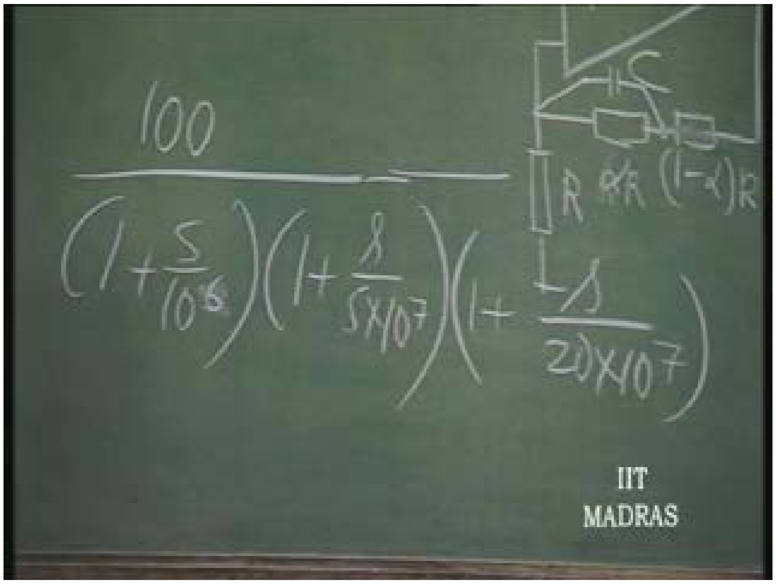

Now, let us see whether this is satisfying the criteria for stability. What does it mean? This magnitude of A Beta should be less than 1 when the phase of A Beta is 180 degree. When will the phase become 180 degree? - at a frequency Omega approximately equal to 5 into 10 to power 7, 20 into 10 to power 7 under the root. It is going to be product of these two frequencies under the root, which is nothing but 10 into 10 to power 7, roughly.

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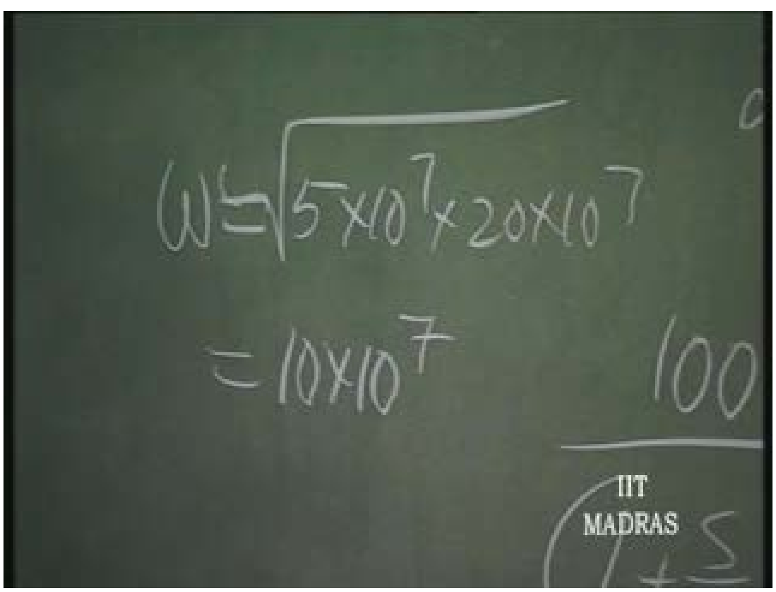

So, at this frequency, there is going to be phase shift becoming equal to 180 degree now. So, what happens? It is 100 divided by 1 plus... now, 1 plus s by 10 to power 6. At this frequency, this 1 can be ignored. So, magnitude of this becomes simply at 10 to power 8 divided by 10 to power 6. So, this itself brings in an attenuation of 100 here.

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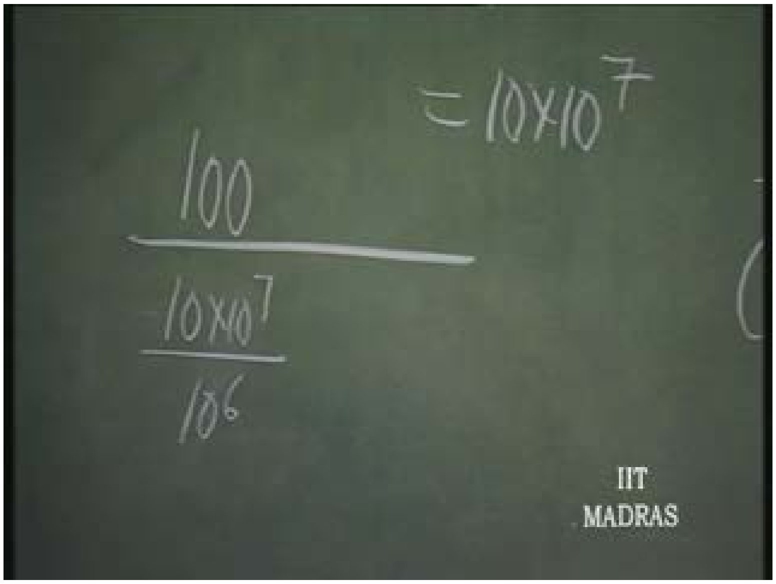

Other things now. 1 plus s is again 10 into 10 to power 7. So, there is a factor of 2 here. So, 2 squared to the power half; 1 plus Omega by this square to the power half. That is the magnitude of this. Then other one is 1 plus half squared to the power half, square.

So, this is the magnitude and obviously this is less than 1. We do not have to calculate because this is 100 by 100 and these factors are greater than 1. So, this is less than 1 and therefore... is less than 1 and therefore stable.

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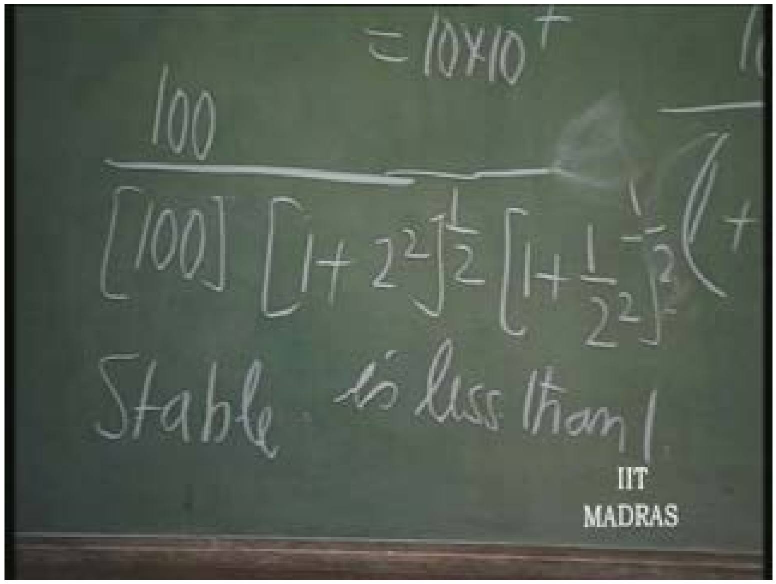

Earlier we saw that this was greater than 1 and it was therefore unstable; and now it is less than 1 and it is therefore perfectly stable; and therefore, there is no problem. We can build this and it has gain bandwidth product which is the same as the original amplifier which we started with; that is 200 into 10 to power 6. That is the gain bandwidth product. That means with a gain of 2, I can use it up to 100 into 10 to power 6. With a gain of 2, bandwidth is going to be 100 into 10 to power 6 so that the gain bandwidth product remains the same.

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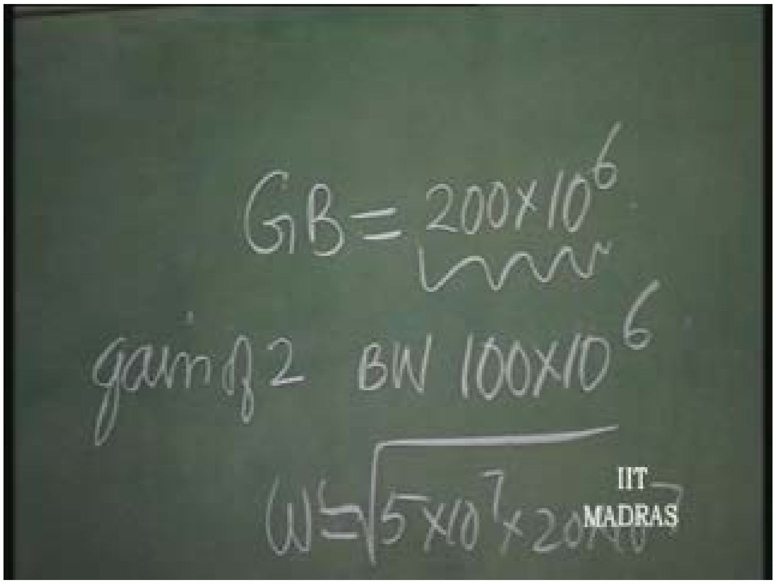

This is the best design possible. For the widest possible frequency range, you can use it as an amplifier with a gain of 2. Now, the question in the previous problem arose as to whether this is unstable for the design given for a Beta equal to half. Only when this is unstable for a Beta equal to half, as it is, that the modification that we have suggested comes into picture.

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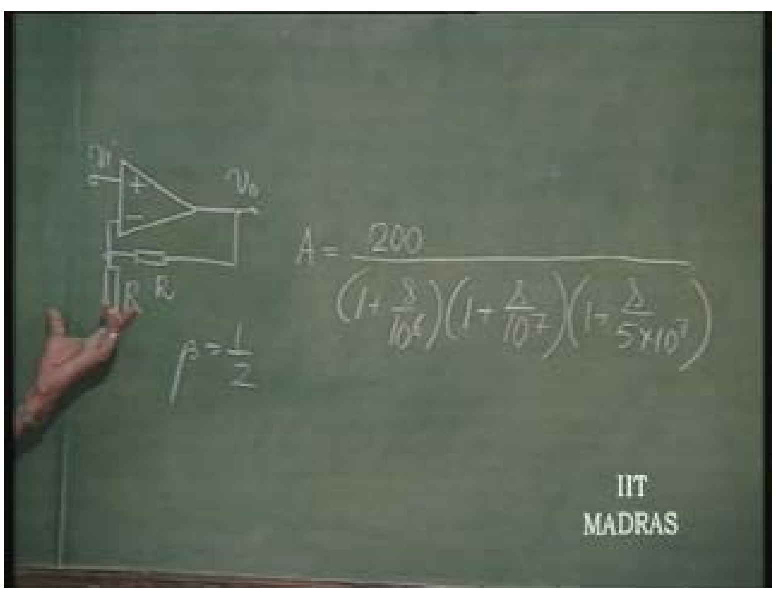

Suppose this is not unstable; then the gain bandwidth product is straightaway available as 200 into 10 to power 6. You do not have to do any frequency compensation. Therefore, let us verify. I had actually given you a problem where A has been so chosen that just as such if we use, it is unstable. Let us make sure that it is unstable; then only the pole zero compensation becomes necessary.

So now, A Beta is going to be 100 divided by 1 plus s to power... s by 10 to power 6, 1 plus s by 10 to power 7, 1 plus s by 5 into 10 to power 7. By cancelling this out and making this become a second pole and introducing a pole far away, we are able to make it stable; but if this itself is stable, there is no need to do this pole compensation at all. Let us see.

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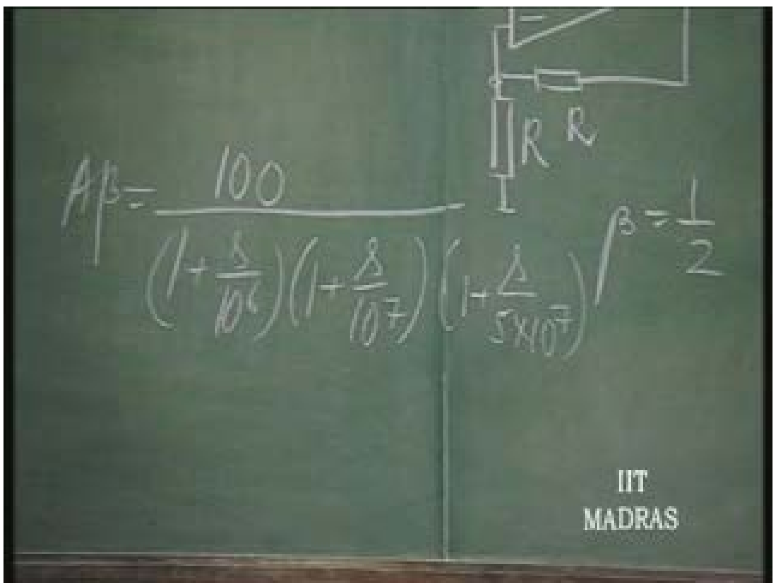

Now the frequency at which the phase shift of this becomes equal to 180 degree is roughly equal to 10 to power 7, 5 into 10 to power 7 under the root, which is root 5 into 10 to power 7.

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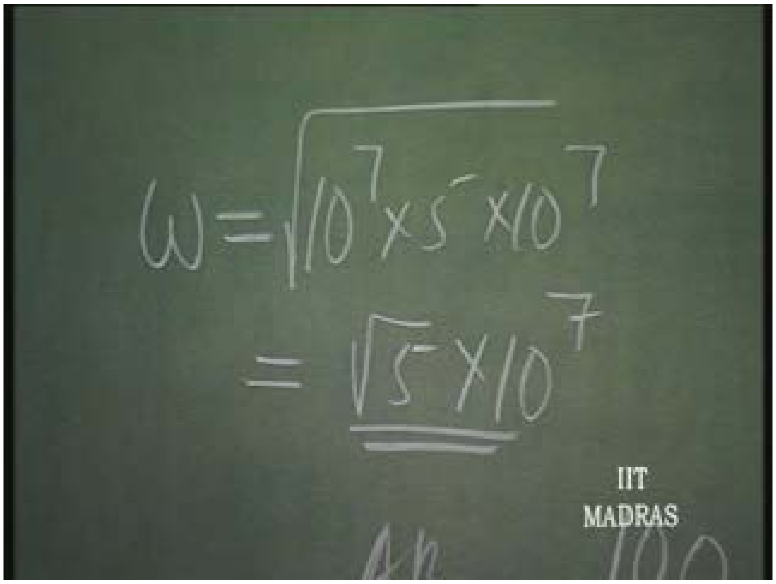

Now, magnitude of A Beta at that frequency equals 100. That is, 200 into half; that is what has become 100 there.

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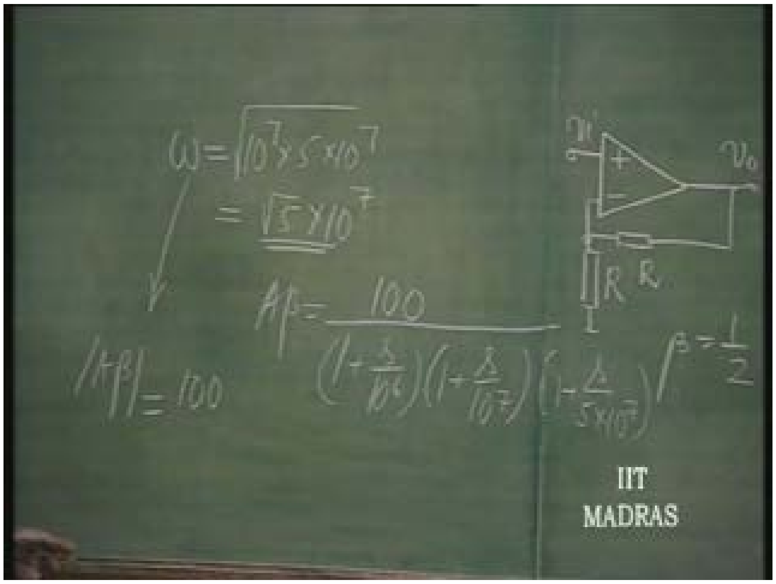

So, that divided by... now this is dominant because it is root 5; so that 1 can be ignored. Root 5 into 10 to power 7 by 10 to power 6; this is the attenuation caused by this pole. That... this is still dominant. At the other pole, this thing is 1 plus... Root 5 into 10 to power 7 by 10 to power 7; root 5 squared. So, 5 to the power half; that is the magnitude of that and then the magnitude of this is 1 plus 1 over 5 to the power half.

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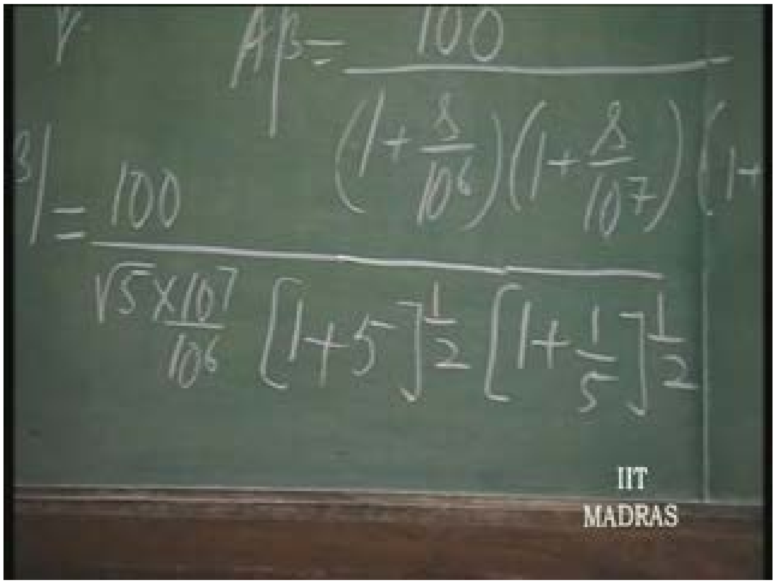

So, you can see that this is greater than 1; this is 100; this is root 5 into 10, which is not much. This is root 6; this is almost nearly 1. So, this is root 30 into 10. So, how much is it? Root 30. So, this is 54 point 7 and this is just root of 1 point 2.

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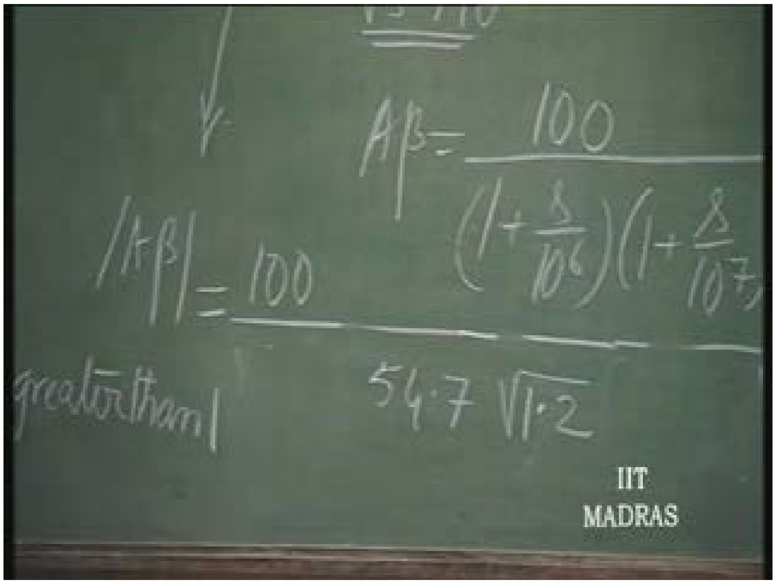

Or, how much this whole thing is? So, you can... so the whole thing is 1 point 67; so greater than 1; and therefore, it obviously needs the kind of frequency compensation, pole zero compensation, that we have introduced.

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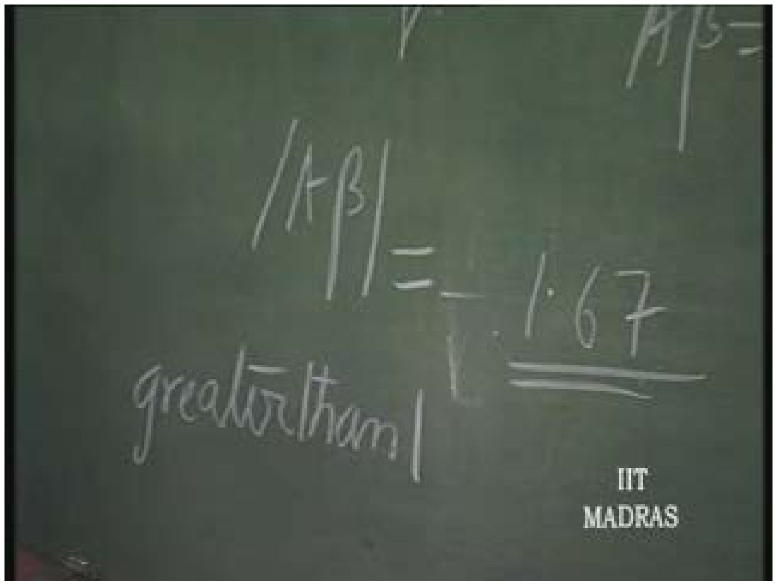

That can be easily introduced in order to retain the gain bandwidth product at 200 into 10 to power 6. So, this kind of wide band amplifier design is commonly adopted when the system is pretty complex. There are more...3 or more poles associated with it. If it is less than 3, if it is 2 or 1, there is absolutely no frequency compensation; and the gain bandwidth product is straightaway the gain into the first pole frequency.

Let us now discuss something about negative feedback and wide band amplifiers and non-negative feedback structures for wide band amplifiers. If I am trying to make the gain insensitive to active parameters, the best way is to give overall feedback with cascaded stages.

That is, you cascade number of stages so that the loop gain becomes very high; D C loop gain becomes very high; and then give overall feedback; then it desensitizes the gain after feedback.

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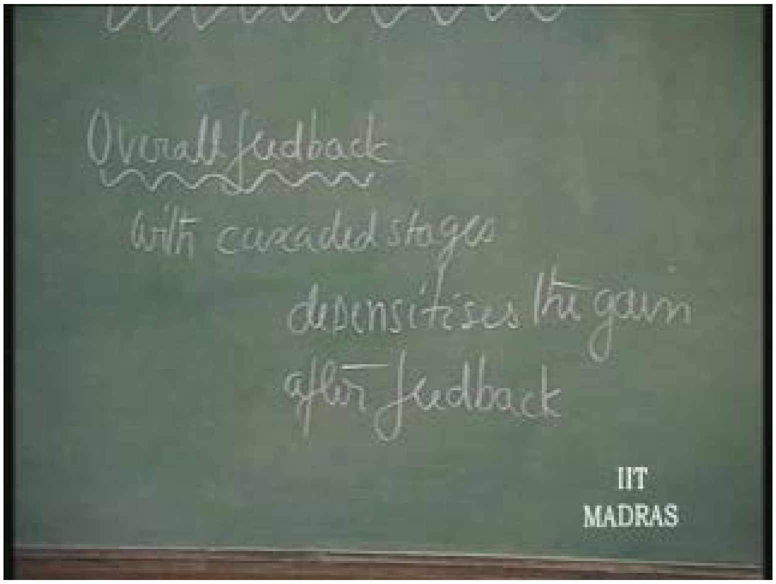

This is the best way to work with overall feedback; but overall feedback always results in multiple poles, results in multiple poles. For example, each stage will have input time constant; that is, input capacitor into input resistor; and output time constant. This is input... capacitance into input resistance; output capacitance into output resistance.

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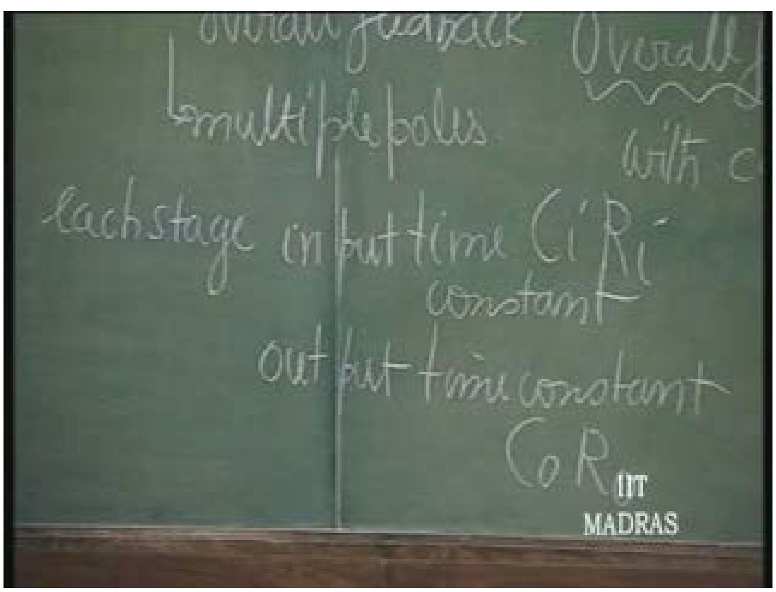

So, both of which will introduce a pole each and Omega p 2 is going to be in whatever transfer function that you are going to obtain from that stage. Primarily, it will introduce an input time constant and an output time constant and introduce two poles.

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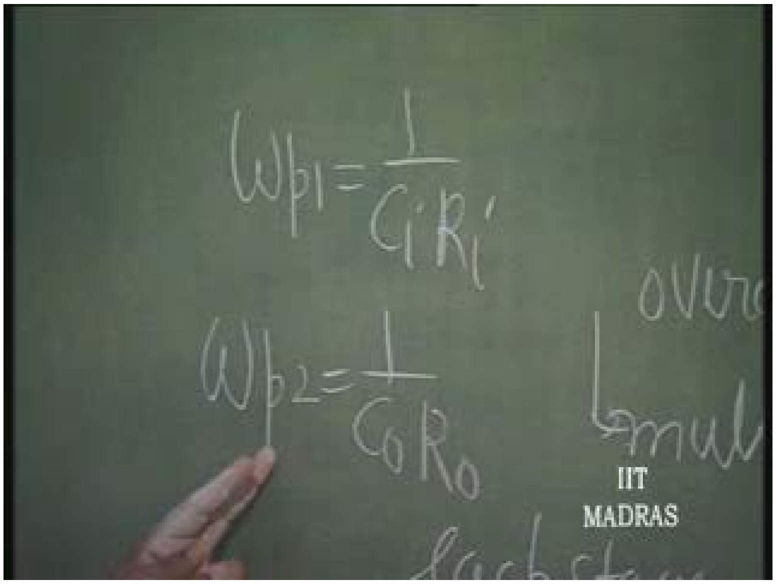

So, each stage will introduce two poles. If there are two stages, there will be minimum of three poles: input, intermediate and output. If there are three stages, there will be four poles. There is one stage, there is likely to be two poles. So, n stages will have at least n plus 1 poles, at least. Other frequency dependent factors may increase the number of poles.

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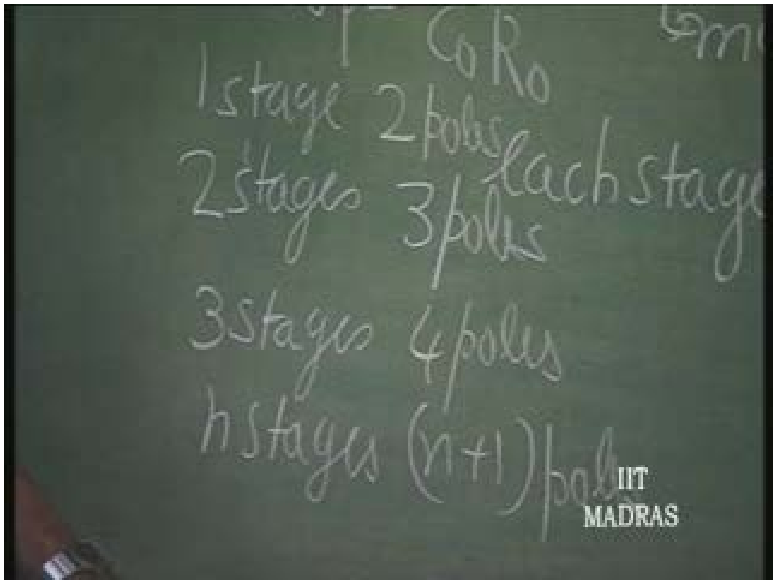

The minimum number of poles, first, one stage will have 2 poles; two stages will have 3 poles; 3 stages will have 4 poles; n stages will have n plus 1 poles. And therefore, we have already seen that we will get into problem, most probably, when we connect two stages because it will result in three poles; and most probably, the frequency compensation may become necessary here; cutting down on the bandwidth may be, if the loop gain is high.

So, definitely in three stages... So normally, overall feedback is not given because of possibility of instability that will arise. Frequency... above two stages. Very rare. So, you will use most of the time, for wide band amplifiers, only one stage, which is pretty safe. A single stage is pretty safe for negative feedback.

So, only local feedback is preferred. Local feedback will necessarily have less loop gain and will be more sensitive to active parameters than overall feedback; but the advantage is that there is no need for frequency compensation. So, it can be a wide band configuration. So, single stage structures are normally preferred for wide band application rather than multiple stages with overall feedback. Multiple stages with local feedback therefore are suited for wide band applications.

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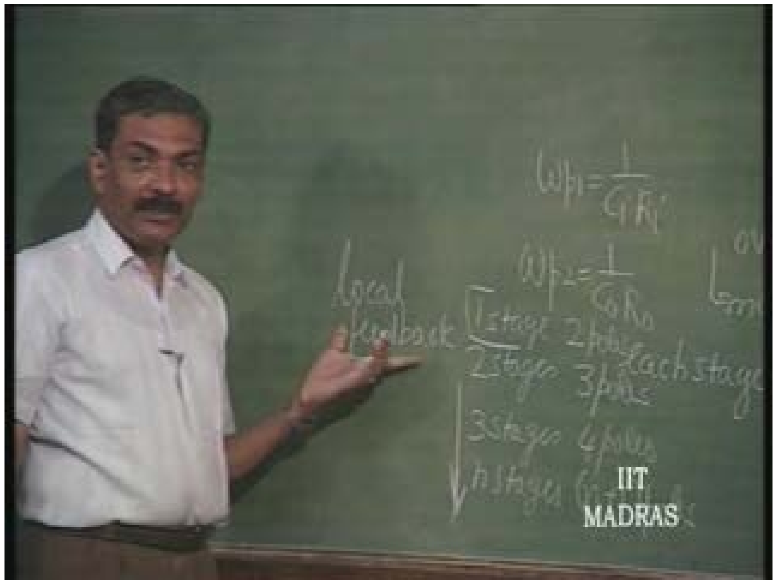

We will therefore now discuss about how to design wide band amplifiers, simple amplifiers and cascade them together to get very wide bandwidth. So, please remember that more than two stages, overall feedback is never adopted because it results in problem of oscillation or instability invariably; and local feedback is resorted. That means single stage will always have negative feedback in order to improve its bandwidth of performance.

When you cascade wide band amplifiers, again remember, that you can prove that overall bandwidth gets reduced. If they are having the same bandwidth and I cascade all the amplifiers together, we had earlier also shown that the overall bandwidth gets reduced because of cascading. So, if you want a certain bandwidth for the cascaded structure, you have to allocate for individual stages, wider bandwidth, than what you ultimately want to have. So, this kind of design is invariably needed in design of wide band amplifiers.

So, let us now consider single stage structures and how to improve bandwidth of single stage amplifiers. So, consider for example, the common emitter amplifier.

When I discuss common emitter amplifier, that discussion is equally well applicable to differential amplifier because a differential amplifier for different signals can be converted into two common emitter amplifiers. So, if you have a common emitter amplifier feeding onto some load here, because of capacitors, there will be input capacitor. In a transistor, this will be the stage capacitor plus the input capacitor of the transistor which is normally called C b dash e; and then there will be capacitor between the base and the collector which is called C b dash c; and there might be some output capacitor here which we will call as C c, collector.

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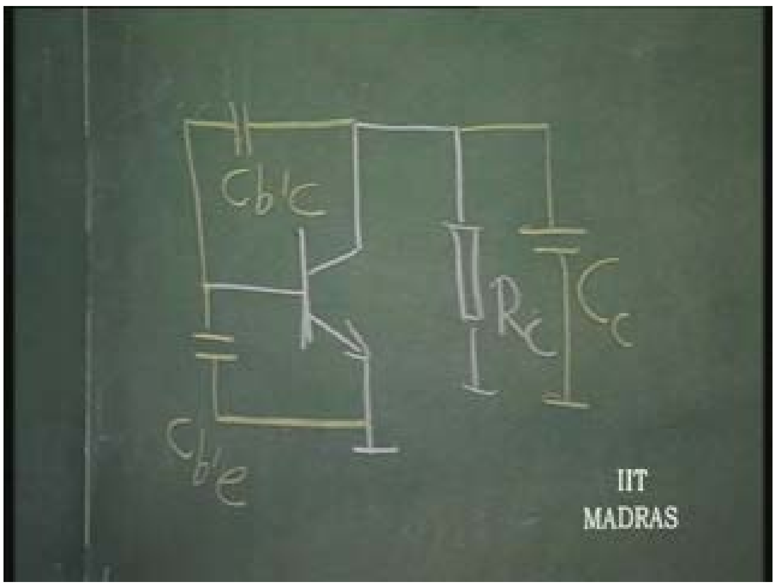

So, what happens in this case is that I can convert this configuration into, approximately, a configuration with two time constants by saying that this particular amplifier has a gain from here. If this V i, this output voltage is going to be minus g m R c into V i; this we have done earlier. g m is equal to 1 over r e, small r e. r e is equal to V T by I E Q. So, this capacitor now appears at the input as a larger capacitor. So, I can convert this capacitor. This is C b dash e; this C b dash e is connecting input to output.

So, if this V i and this is g m times...minus g m times R c times V i, then the current in this is V i plus g m R c V i into s C b dash c. That is admittance. That is the current in this circuit.

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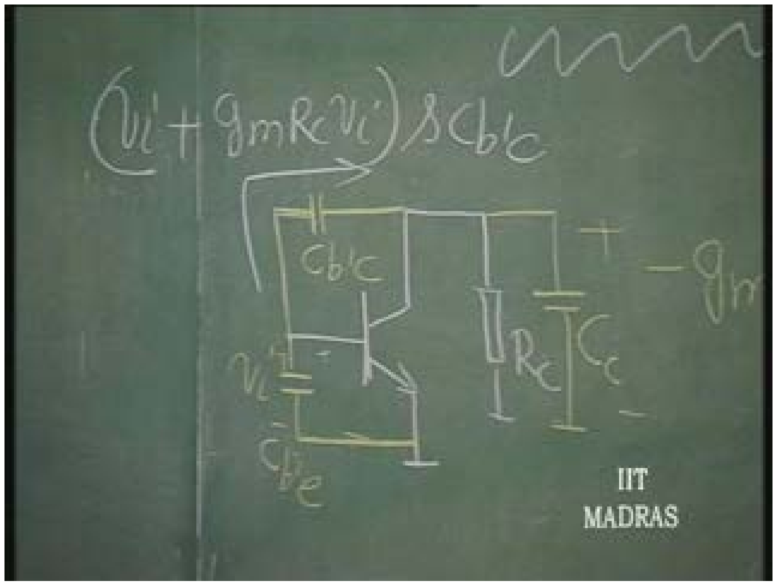

So, as far as V i is concerned, it is going to appear as... this is going to be the current. That is going to be down. So, V i by I i is going to be 1 over s C b dash c into 1 plus g m R c.

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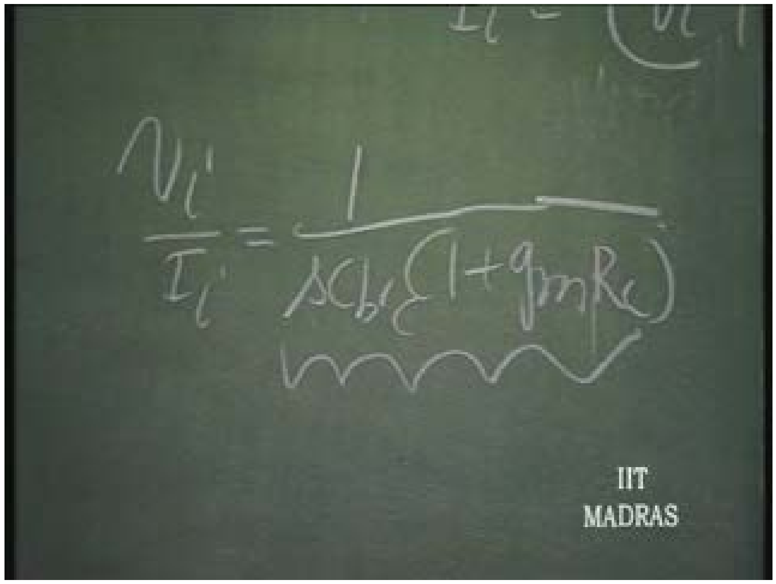

So effectively, you get a capacitance which is C b dash c into 1 plus g m into R c. This is important phenomenon. This is called Miller effect. This capacitor is called Miller capacitor and this is called Miller effect.

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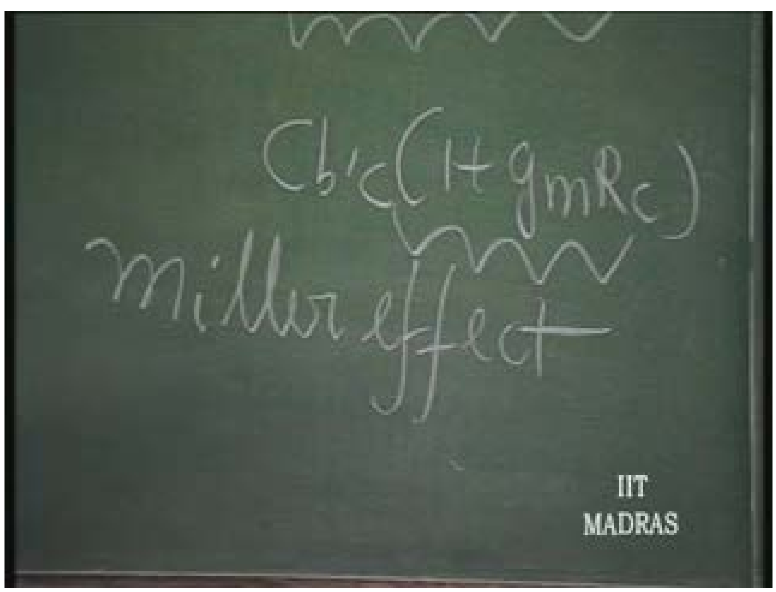

Any amplifier which has a capacitance between its input and output, that capacitance gets amplified by a factor of 1 plus gain. That is the miller effect. So effectively, the input capacitor C i is going to be C b dash e, input capacitor, plus C b dash c plus into 1 plus g m into R c; and as far as the output is concerned, output is g m R c times higher than the input. So, this capacitor is going to be appearing as C b dash c plus 1 by g m R c so that is very high. So, it is very essentially going to appear as C b dash c.

So, output capacitor is going to be C c plus C b dash, approximately; and the input capacitor... because input is going to be amplified here as minus g m times R C, the current is going to be more. So, output capacitor is essentially, C naught is equal to C c plus C b dash c. Input capacitor is C b dash c plus C b dash c plus...

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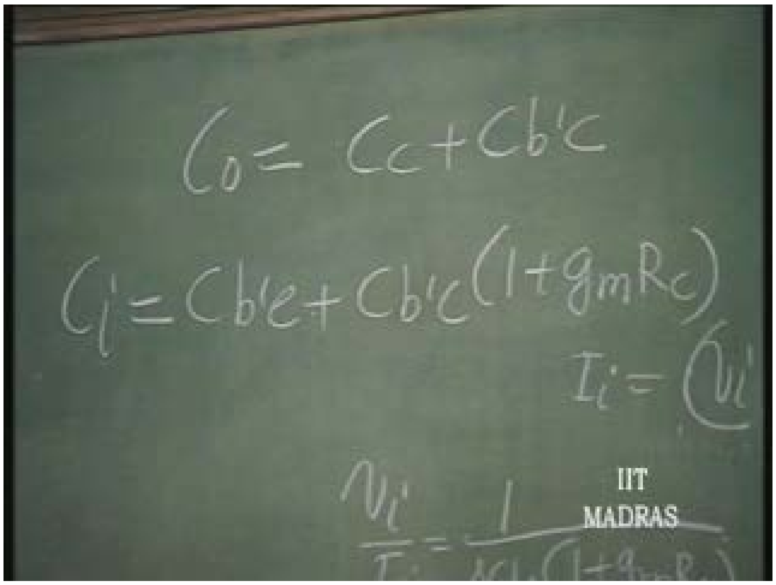

So, we have now a means; whether it is a field effect resistor or bipolar transistor, same thing is applicable. Those capacitors are the culprits in bringing down the bandwidth. So essentially, as far as this common emitter amplifier is concerned, Omega p 1 is going to be the pole. If you consider this, R i C i... What is R i? That we know. That is the common emitter amplifier. r e into 1 plus Beta – that is the input resistance. That into C i which is C b dash e plus C b dash c plus 1 plus g m; that is R c divided by r e. So, this is the pole of the common emitter amplifier. Because of Miller effect, this capacitance is boosted up.

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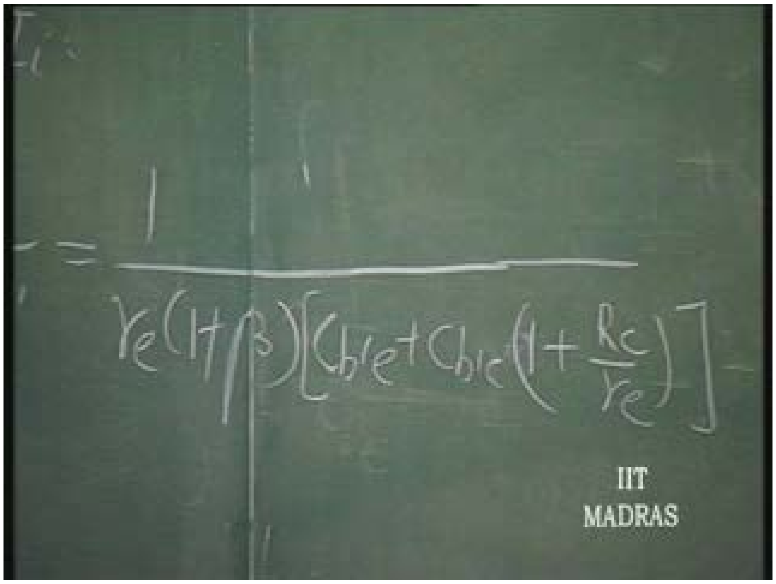

The output time constant Omega p 2, 1 over R naught C naught which is roughly 1 by, output impedance of structure if is very high, it is essentially R c into C naught, which is C c plus C b dash c.

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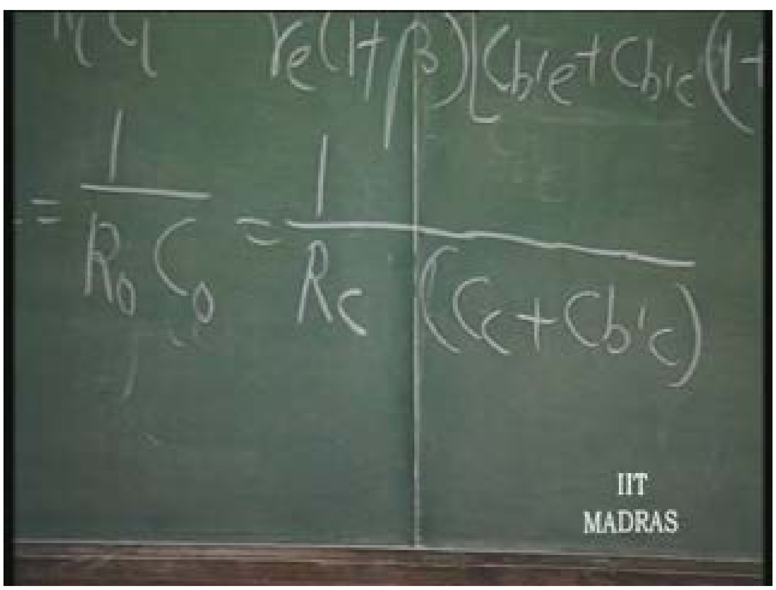

You can see therefore that if R c is of the same order as r e into Beta plus 1, normally, Omega p 1 becomes the dominant pole because this capacitor is going to be very huge compared to this capacitor. So, it is normally the input time constant which fixes up the dominant pole in a common emitter amplifier. So, whether it is a common emitter amplifier or common source amplifier, same thing is applicable.

So, you can therefore see here that the bandwidth of the common emitter amplifier is nothing but Omega p 1 in most of the cases. Bandwidth of the common emitter amplifier is Omega p 1. r e is V T divided by I E Q. This we know. Now, bandwidth of common emitter amplifier is this. How to improve this bandwidth further? This is our purpose of our discussion in this wide band amplifier category.

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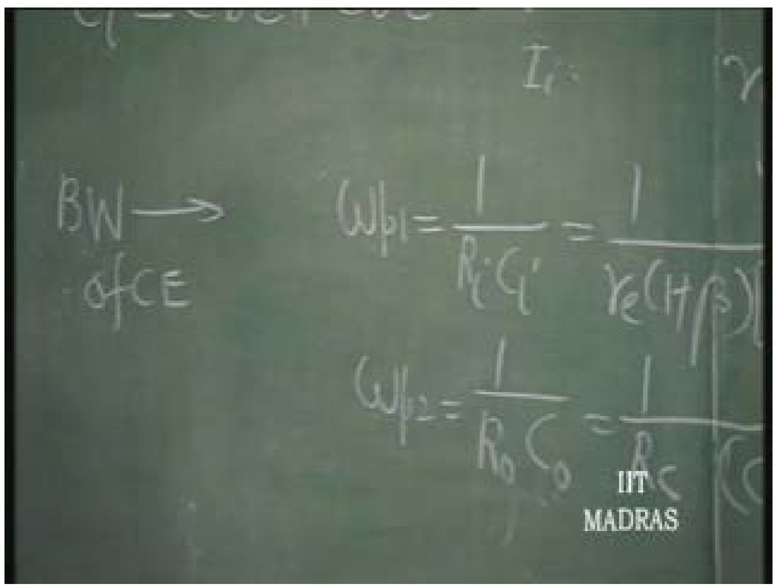

Obviously, I cannot do anything about this. I have to somehow reduce the effect of the capacitor. For that purpose, what I do is... Common emitter amplifier - let it have low voltage gain. So, what do you do? I will now feed this into another common base structure. This is the common base structure. So, this current is going to be going into the common base structure input current. So, output current is same as this. So, there is no difference as far as low frequency picture is concerned, because this current is going to be same as this current; and I can put R c here because the common base has a current gain of 1.

So, as far as I am concerned, nothing has happened for the low frequency performance. This particular current is now going to flow into this r e and is going to appear as Alpha times that current. So, and now, it is going through r c. Earlier, it was going into r c. So, as far as this structure is concerned, the gain still remains as g m into R c; minus g m into R c, because even the phase has not changed.

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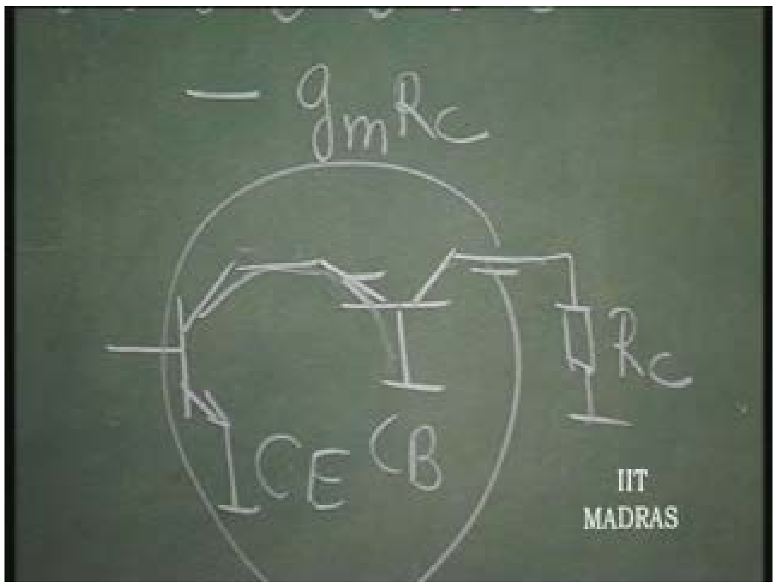

So, this configuration of cascading common emitter with common base is called, a special structure called, cascode which is one of the most popular wide band structures. Why wide band? How did it get wide band. This wide band comes because of cross impedance mismatch here. This... earlier was directly going into R c which was, may be very high, but now it is going into small r e.

So, what will be the gain of this now? This Miller effect is reduced because this r c is gone here. As far as this stage is concerned, R c is not there. So, this is r e itself; they are operating at the same current. So earlier, R c over r e was very high. Now it becomes r e over r e.

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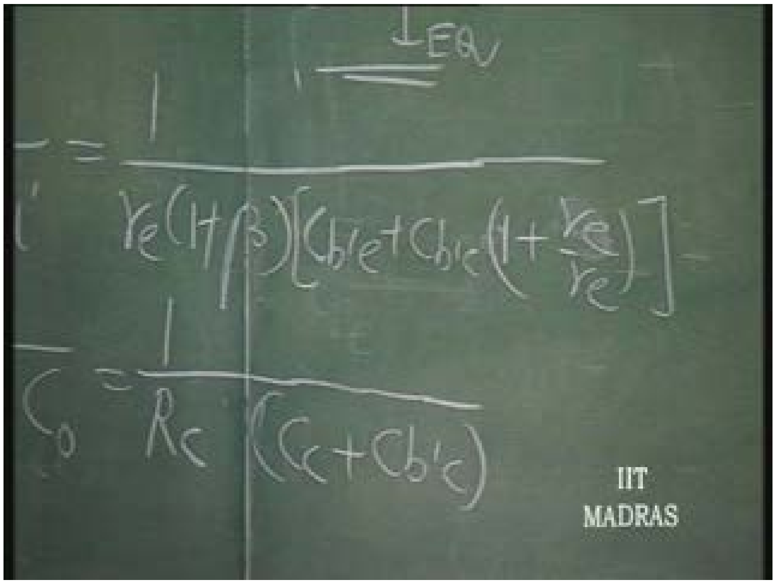

So, because it becomes simply two times C b dash c.

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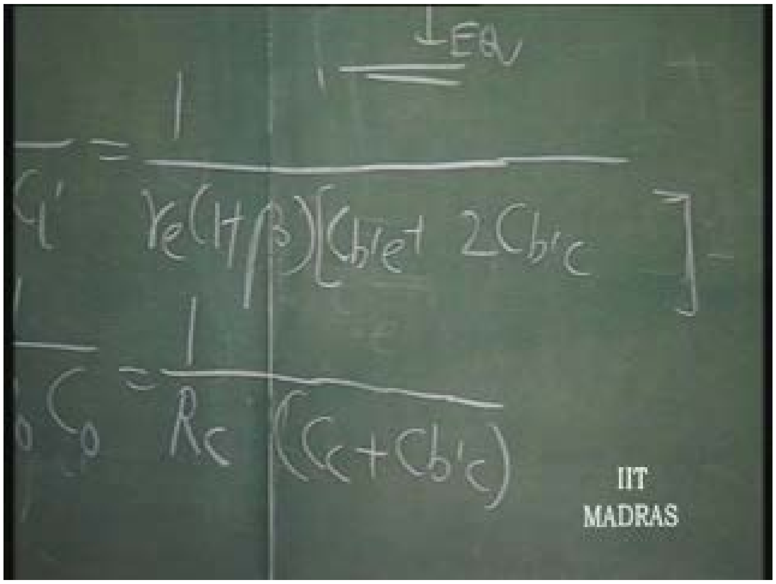

So, bandwidth of now cascode simply goes up; may be, this particular thing is still dominant. We do not know because this capacitor may be still fairly high compared to C b dash c; but the bandwidth here has improved enormously. As far as the low frequency gain is concerned, it still remains g m into R c.

So, I can now write down the complete expression for the gain.

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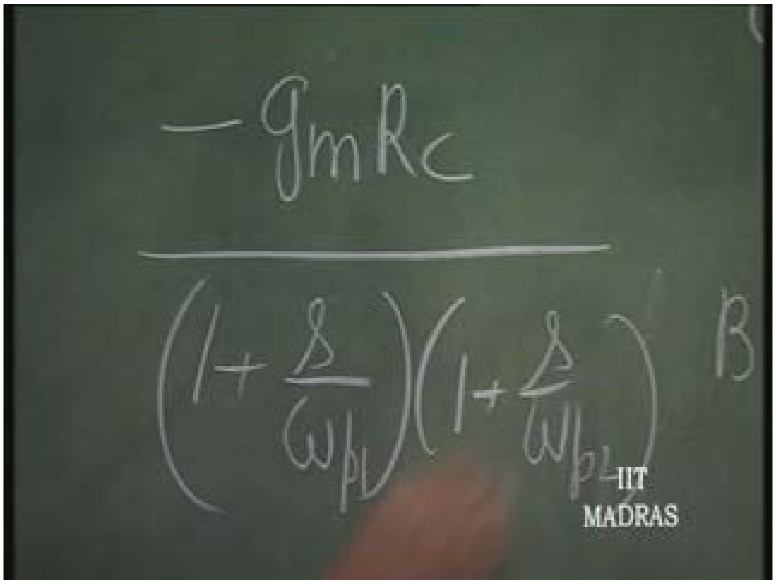

Omega p 1 and Omega p 2 being these two for the cascode structure. Again, the low frequency gain remains the same. Earlier, of course, it was being replaced by 1 plus g m into R c. That is the expression for the gain; complete expression for the gain. So, bandwidth is still equal to Omega p 1; it has improved drastically.

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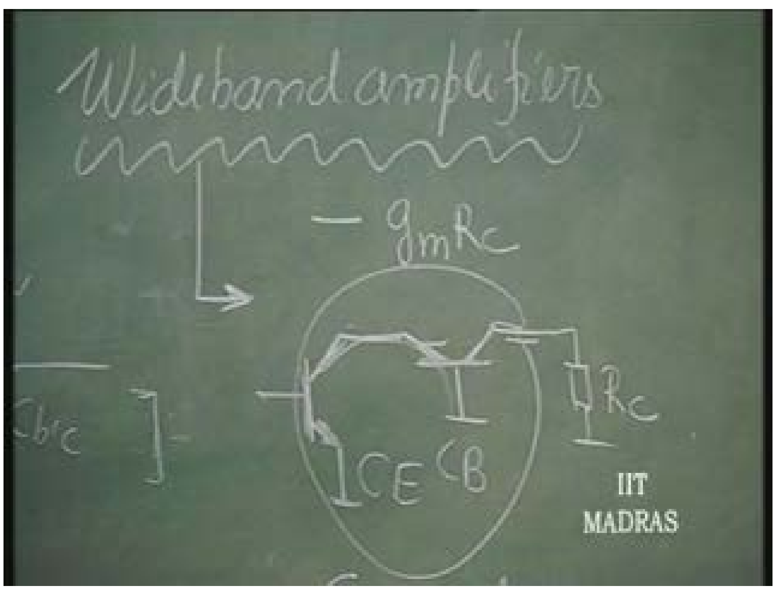

So, this is a wide band amplifier; a cascode structure which is nothing but a common base cascaded to common, common emitter cascaded to common base.