Analog Electronic Circuits
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Lecture - 34
Unity Gain Bandwidth

Welcome back to analogue electronics. Today's lecture number 34 is going to be about unity gain bandwidth. So, this is what we were discussing. In the last class, but we had started talking about it very briefly.

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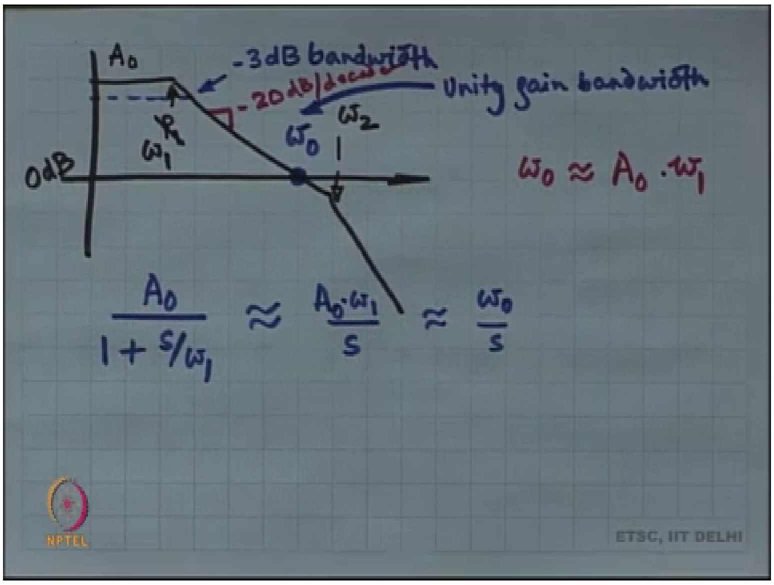

The idea is that if you look back at the bode plot; you have a system that is going to look like this. This is the open loop Op-Amp.

It is a 2 pole system, probably with 0 that you have right half plain 0 that you have cancelled out. So, you be do not bother about the 0 over here, right. You got a pole P 1 and you have got another pole, not P 1 we called it omega 1 is it, omega 1, and you have got another pole omega 2. And in between you have this point omega naught, and at this point the gain the Op-Amp at this frequency the gain of the Op-Amp is 1 or 0 dB. So, this is called the unity gain bandwidth. The gain at which the amplifier has unity gain the frequency, the bandwidth for which the amplifier has gain more than unity, alright.

Now, commonly used bandwidth expressions are minus 3 dB bandwidth ok. That is going to be over here right. And the other one is unity gain bandwidth. Now there is something special about the unity gain bandwidth, something very special, and we are soon going to see what it is. For now, you have to realise that if you do not worry about omega 2, then the relationship between omega 1 and omega 0 is; what is the relationship between omega 1 and omega 0? Yeah, what is the relationship? At omega 1 the gain was A naught right, and then the gain started dropping at 20 dB per decade.

20 dB per decade means, If the frequency increases 10 times then the gain decreases 10 times. If the frequency increases x times, then the gain is going to decrease x times. At omega 0 the gain has decreased A naught times, the gain is now 1. So, earlier gain was A naught, at omega 1, at omega 0 the gain is 1. So, the gain has decreased x times; which means that the frequency has increased the same A naught times. So, therefore, omega 1 omega 0 is approximately A naught times omega 1.

Now, the system could have been expressed as A naught divided by 1 plus s by omega 1, if you do not worry about omega 2, omega 2 is much higher than everything else. Remember, this is you know logarithmic scale; so, little bit here and there is a large leap. If this was your overall approximate transfer function, then you could say that omega 1 is a very small frequency, right omega 1 is usually a small frequency. And for all reasonably large frequencies like omega naught and so on right all these reasonably large frequencies.

S by omega 1, s is where you are going to plug in the frequency. J times the frequency is s. So, s by omega 1 is going to be significantly larger than 1. At those frequencies and in such a scenario you can start ignoring the 1. And you can approximate this as A naught times omega 1 by s, and A not by times omega 1 is nothing but,. So, this is the overall setup alright. So, the entire system can be simplified by virtue of the fact that the first pole is a very low frequency. So, whenever you are talking about any frequency, that frequency is going to be typically larger than the first pole because the first pole is a very low frequency.

Few a 100 hertz tens of hertz; if you buy a commercial Op-Amp of the shelf, it is a few hertz, omega 1 is just a few hertz, 5 hertz, 10 hertz something like that, ok. So, any reasonable frequency is going to be above omega 1. And therefore, the amplifier can be expressed as nothing but omega naught by s where omega naught not is the unity gain bandwidth, alright. Now let us look at a few systems. One popular system your favourite amplifier Op-Amp circuit is this one.

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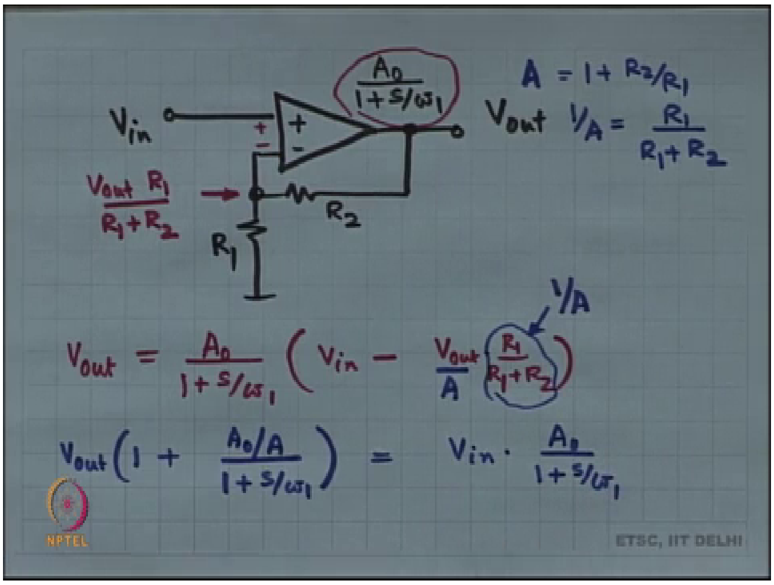

Ok and you know that the gain of this system. V in, V out you know the nominally the gain of this system V out by V in is 1 plus R 2 by R 1 we know this for a fact. Now the Op-Amp is no longer our lovely Op-Amp, we are going to replace the Op-Amp with it is transfer function. And the transfer function let us say the transfer function is A naught by 1 plus s by omega 1 right, omega 2 is much larger. So, I am not going to worry about it. So, this is my amplifier alright. Now what is the voltage over here ? Let us analyse, we need to find out the relationship between V in and V out, given that the Op-Amp does not have infinite gain anymore, it has a gain which is this one.

Right, it is a function of frequency and it has limited gain. So, let us try to analyse the system. We have V out over here; the voltage over here is V out into R 1 by R 1 plus R 2, fine. Resistive division, potentiometric division; so, the voltage difference between these 2 is V in minus this quantity. And that is going to be amplified by this factor and you are going to get V out. So, therefore, you can write an expression V out is equal to A naught by 1 plus s by omega 1 times V in minus V out times R 1 by R 1 plus R 2, fine.

Now, just pause over here a little bit. I am going to call the nominal gain of the amplifier of this circuit. The nominal gain was 1 plus R 2 by R 1, remember. So, I am just going to call that as A, ok. That is the nominal gain of this circuit. That is the gain that you desired right. Let us call that A what is 1 by A right? So far so, good this makes sense because you are comparing V in with V out divided by A. If V out divided by A is equal to V in right, then only it works, these 2 have to be equal. So, therefore, these 2 are this one has to be equal to V out divided by A. So, that the error is 0 ok.

Now, let us solve, we have to solve for V out by V in. So, will take all the V out related terms on one side, and we are going to keep all the V in related terms on the other side. And this is what we get gathered collected all the V out terms on one side V in terms on the other side.

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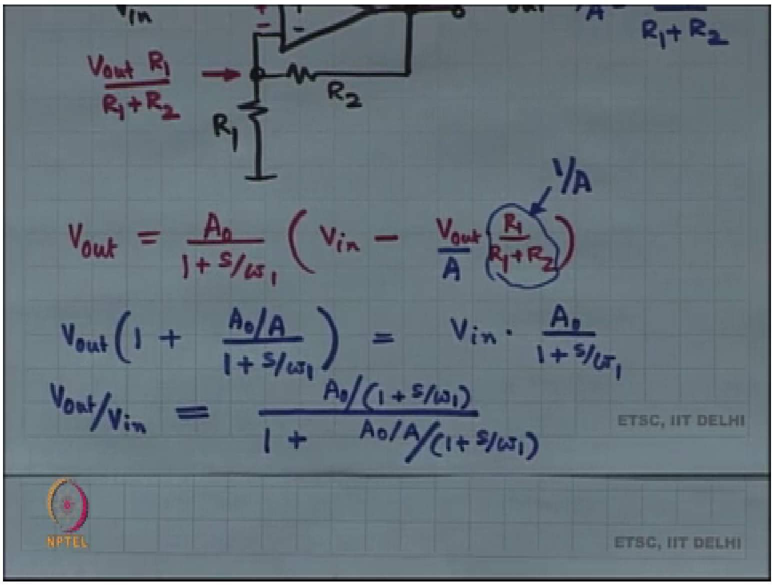

And now we are only interested in V out by V in, ok. And your natural instinct is going to be to multiply numerator and denominator by 1 plus s by omega 1.

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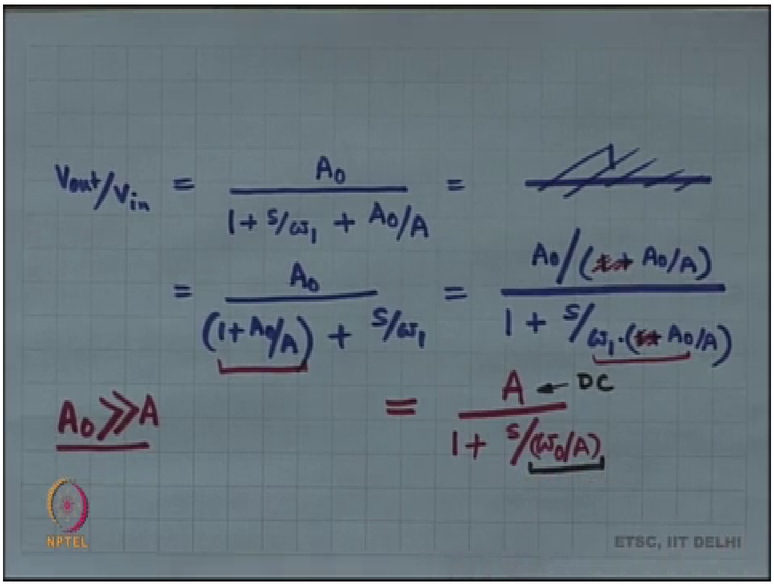

You want to simplify further? I think so, I think a little bit more can be done we can multiply numerator and denominator by A not even not even that. We can divide numerator and denominator by A naught.

No, not even that you see the way we work is that the denominator should look like 1 plus s times something. That was a template. So, I am sorry we should not deviate from the template. So, what we have got is A naught by 1 plus A naught by A plus s by omega 1 right, this is what we have got. The denominator should look like 1 plus s time something. So, therefore, we should divide numerator and denominator by this factor. Is this ok? Now let us think about it for a little bit. A naught is a large quantity 10,000, ok.

A is a relatively small quantity; you are going to make a limited gain amplifier circuit over here, right. You are going to make a gain of 10, gain of 15, something some limited number. It is not going to be certainly not going to be more than the Op-Amp gain, it cannot be more than the Op-Amp gain, it is going to be significantly lesser than the Op-Amp gain such that the circuit works, right. So, A is substantially smaller than A naught, A naught by A is going to be a substantially large number; in which case 1 plus A naught by A is more or less equal to A naught by A.

So, you can stop worrying about this one portion right. You can stop worrying about this one portion. You see in engineering, it is important to stop worrying about the small things, you look at the big picture over here. It is not maths, this is engineering. So, then we can simplify a little bit further, and what happens? A naught and A naught cancel out, very politely, and all you get is a divided by 1 plus s by omega 1 A naught what is omega 1 times A naught, omega 1 times A naught A is the unity gain bandwidth, omega naught by A, alright.

So, this is what we have. What does this mean? This means that A DC at 0 frequency, this s term is irrelevant at 0 frequency, and all that you are left with is A at DC. You were trying to make an amplifier of gain A, your left with a gain A at DC perfect, right. Of course, the gain was not exactly a it was A naught by 1 plus A naught by A which I have simplified to A by assuming that A naught is much larger than A. And unless you make this assumption you will not get that perfect gain of a, that you wanted. So, a certainly has to be much much much smaller than A naught for this 2 what ok. If you if you have not chosen a to be much smaller than A naught, then I am sorry you are circuit is not going to give you the desired performance right.

Now, this is the performance at DC ok. What is the bandwidth? What is the 3 dB bandwidth of the system? The 3 dB bandwidth of the system is not related to omega 1 it is related to omega naught, the unity gain bandwidth, it is the unity gain bandwidth divided by A.

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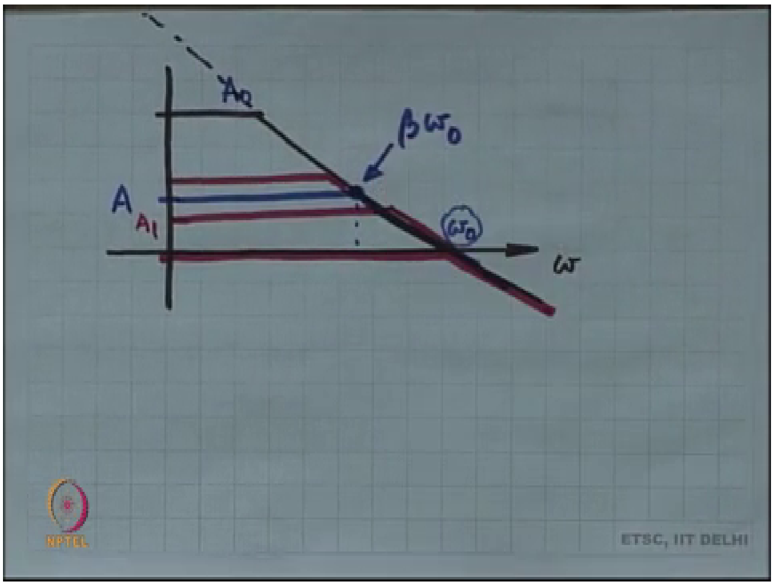

So, let us go back a little bit. I had my system ok, this was my unity gain bandwidth. I start from a DC gain A naught. Actually the value of A naught is irrelevant, right you could have started anywhere on this curve.

Now, you are saying that I make this beautiful circuit, alright and this circuit has a nominal gain of a at DC. Let us put a over here, a has got to be smaller, substantially smaller than A naught. And guess what, the 3 dB bandwidth of the system is omega naught by A, ok. It is right at this corner; how do you know that right side the corner? Because if I decrease the frequency by omega naught the gain increases by A ok. So, at the frequency omega naught by A the gain is A. So, it is right at this corner alright, any other system suppose instead of a, you design your circuit to have a gain of A 1.

Suppose A 1 is this one, what is the bandwidth going to be? What is the characteristics going to look like? It is going to look like this. Right will have the same overlapping characteristics, whatever system, you design it is going to have the same overlapping characteristics ok. And the overlap depends on the value of omega naught, the unity gain bandwidth. Suppose your a was equal to 1, maybe right A could be chosen to be one, you could make your circuit to have a gain of one we have we know some utility of having a gain of one, right. It is useful in that case the system will just look like this.

And it will have a bandwidth a 3 dB bandwidth of omega naught, alright. So, that is why this unity gain bandwidth is so important, right. Whatever system you are going to design, when you look at the thee dB bandwidth of that system, eventually it is going to be related to the unity gain bandwidth of the base amp, the core amplifier the core Op-Amp, that is being used inside that system, alright. Now in our analysis, we ignore this 1 plus As soon as you ignore the 1 plus you can start calling it calling the Op-Amp as omega naught by s.

So, when you have a lot of Op-Amps in the system, you can approximate all the Op-Amps, as omega naught by s and that will give you a quicker answer to the problem, let us do one more.

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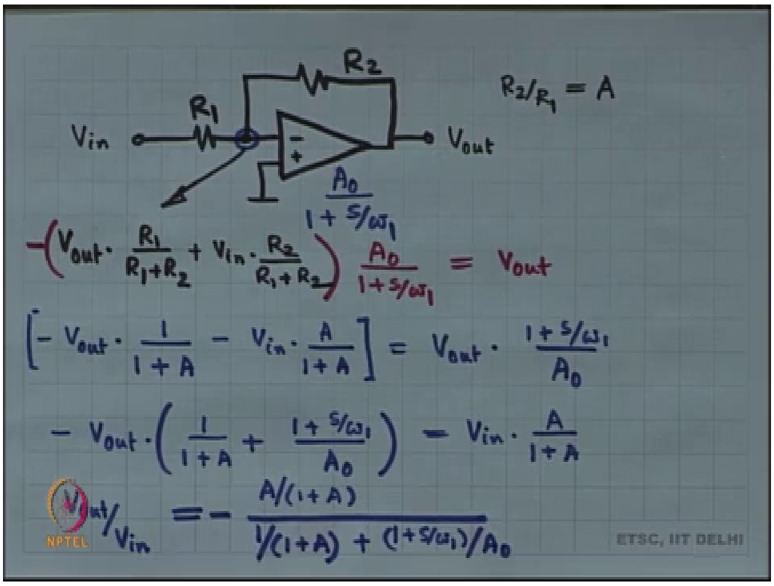

Let us do one more of your second favourite circuit was inverting amplifier, ok. And here we are going to choose R to by R 1 is equal to the gain, ok. So, here the gain is minus A in this case, fine. Now unfortunately the same result is not quite work.

. So, let us do it. Let us do it; we need to do it to appreciate that the same result does not quite work. It is going to be similar, but not exactly the same. And then will generalized from there. What did we do last time? We said that the amplifier has a response that looks like this, ok. So, will start from this, and what is the voltage over here? The voltage over there is related to V out and V in, ok. So, how did I do this?

So, quickly I did it by inspection with the help of superposition. So, forget the Op-Amp over here, first I assume that V out is there, V in this ground, in which case it is a potential divider right, a value R 1 by R 1 plus R 2. In the next case, I I imagined that V in is there, V out is ground, in which case it is a potential divider again, with R 2 by R 1 plus R 2, ok. So, it is V out times R 1 by R 1 plus R 2, plus V in times R 2 by R 1 plus R 2. That is the voltage over here. This voltage minus of this voltage in fact, is the difference between plus and minus, times the gain of the Op-Amp is equal to V out. Fine, so far so good?.

This is fine, but I want to write down R 2 by R 1 to be equal to A, alright. So, let us simplify a little bit ok. I just divided numerator and denominator by R 1, and here I am going to divide numerator and denominator by R 1. And then, again you need to collect all the V out terms together, all the V in terms together, ok. And then finally, you have to find out V out by V in ok. You see the maths is no longer the same as before, but anyway let us proceed. Instinct would say that let us multiply numerator and denominator by A naught times 1 plus A.

So, I am multiplying numerator and denominator by A naught times 1 plus A. Fine, so far so good?

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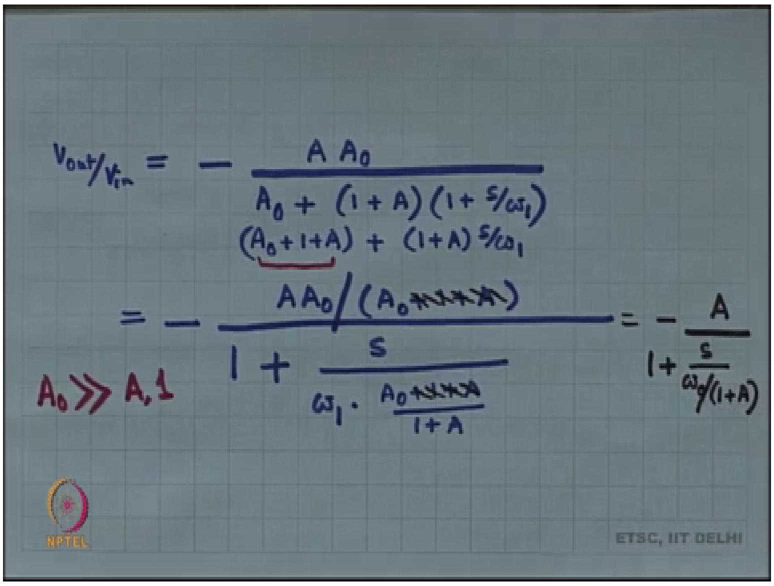

Ok, what you do a sanity check ok, you can do a sanity check, you just plug in s is equal to 0, if I plug in s is equal to 0, this disappears. So, the denominator becomes A naught plus 1 plus A, and A naught is substantially larger than both 1 as well as a which means this whole thing can be thrown out. In which case you get A times A naught divided by A naught which is just minus A.

So, it works the sanity check says that we are on the right track we haven't made a mistake, while doing our calculation. So, this is always very important, sometimes you should pause, and check your answer, right. There are easy ways to check your answer, alright. Next what are we going to do? We need to make sure that the denominator is of the form 1 plus something. Ok right now, the denominator is A naught plus 1 plus A plus 1 plus A times s by omega 1, right this is what the denominator is right now. We do not like it, right we want to make it 1 plus s times something ok.

And what does that mean? That means, numerator and denominator have to be divided by this factor. So, let us do that, and this is what we have, alright. Now once again you can approximate A naught plus 1 plus A to be approximately A naught, assuming that A naught is much much much larger then both a as well as 1,. You do that, then these portions disappear in which case this boils down to A times A naught by A naught is approximately A divided by 1 plus s by omega 1 times A naught is, omega 1 times A naught is the unity gain bandwidth omega naught ok.

And what does that mean? That means, that my gain is approximately minus A which is perfect. But the bandwidth the 3 dB bandwidth is omega naught by 1 plus A, what happened here?

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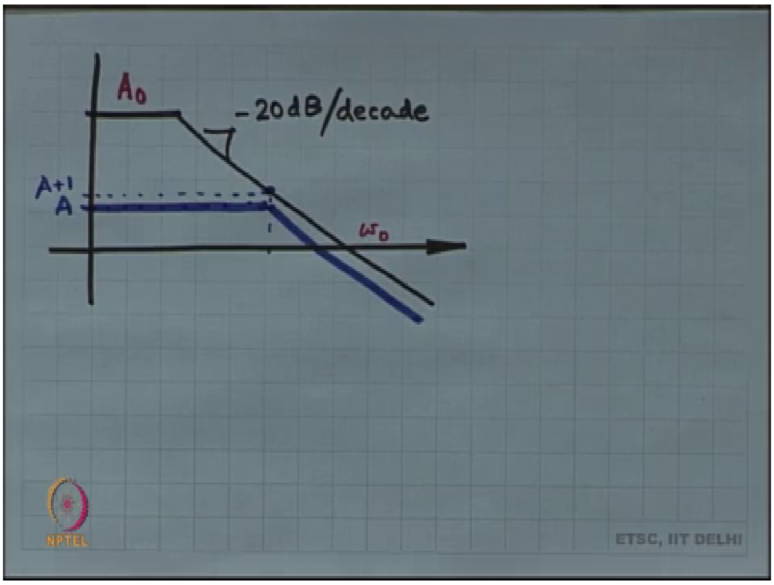

So, if you do a bode plot is started from A naught at omega naught you had your unity gain frequency, and then you are saying that let us build a system with a gain of A, ok. So, you start building a system with a gain of A, but the bandwidth that we have is equivalent to omega naught which is the unity gain bandwidth divided by 1 plus A.

So, not exactly omega naught by A, because omega naught by A would have been this corner frequency, not quite right our corner frequency is that for which you start with A plus 1 ok. So, this corner frequency is going to be used. So, it does not exactly overlap, it is almost there ok. Instead of dividing by A the bandwidth you are dividing the bandwidth by A plus 1. So, it is a slightly smaller bandwidth where did A plus 1 come here. So, in our first circuit the [vocalised-noise] the non-inverting amplifier, we got a nice gain of sorry, a nice bandwidth of A times smaller.

Right in this circuit the bandwidth of the whole circuit the bandwidth of the Op-Amp is the unity gain bandwidth of the Op-Amp is omega naught. The 3 dB bandwidth of the Op-Amp is omega 1, which is a tiny frequency. But the bandwidth the 3 dB bandwidth of the whole circuit is something which is related to not related to omega 1 at all, it is related to the unity gain bandwidth omega naught, it is the gain of this circuit times smaller than omega naught, ok. So, if you had chosen a gain of 5, then the bandwidth 3 dB bandwidth of the whole circuit would be 5 times smaller than the unity gain bandwidth, ok.

In fact, gain times the bandwidth is a constant 5 times n omega naught by 5 is omega naught. Gain times bandwidth happens to be a constant in this circuit. This inverting amplifier is slightly different right, what did we get in this inverting amplifier? We got it to be slightly different, we got it as if the amplifier has a gain of A naught, and a bandwidth of omega 1, then it has a unity gain bandwidth of omega naught which is A times omega 1, A naught times omega 1. Now I plug this into a circuit to make a gain of A.

The bandwidth of the circuit is going to be omega naught divided by 1 plus A. Now where is this 1 plus A coming in from? Ok, that is where it is coming from this one A you see there is 1 plus A everywhere. It is not just A, it is 1 plus A. By the way A is not a gigantic number, ok. A can be a small number, A can be 1, A can be 2. So, 1 plus A cannot be approximated as A. But 1 plus A naught can be approximated as A naught ok. Because A naught is always very large it is 10,000, 100,000,.

So, this 1 plus A is coming right from here, right it is coming from this ratios, these 2 ratios that we made right. In fact, 1 by 1 plus A is nothing but R 1 by R 1 plus R 2. How did we get R 1 by R 1 plus R 2, right? The sum of these 2 resistors, R 1 plus R 2 and this R 1. So, 1 by 1 plus A is called the feedback factor ok, in popular word name in the literature this is called as the feedback factor.

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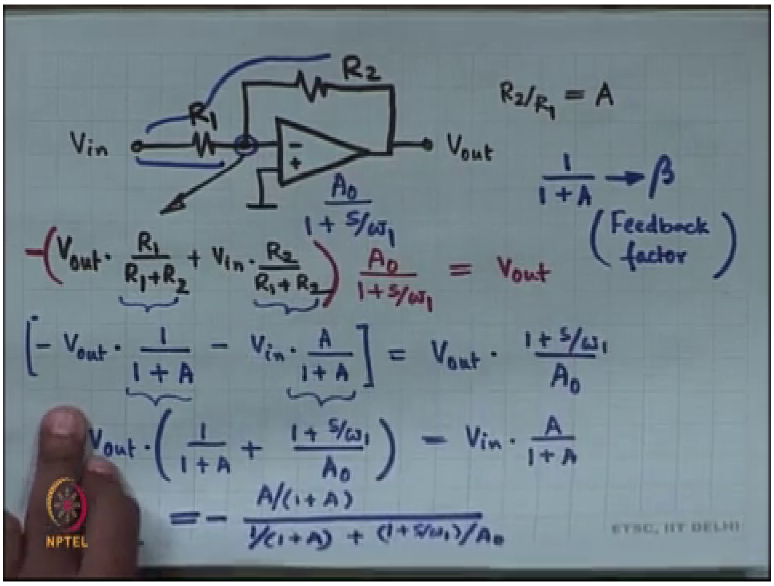

So, this is called as beta lot of people call it as beta defined as the feedback factor. What does it mean? It means I take V out; what portion of V out is fed back? It is beta times V out that is fed back, alright.

And in such a case, you could write this as minus A by 1 plus s by omega naught times 1 by 1 plus A; so, omega not times beta. So, the bandwidth changes by the factor beta whatever that factor is. Now this happens to be general enough. If you look at the feedback factor in the first circuit, what happens? V out what portion of V out is fed back; it is V out times R 1 by R 1 plus R 2. So, R 1 by R 1 plus R 2 is going to be called beta.

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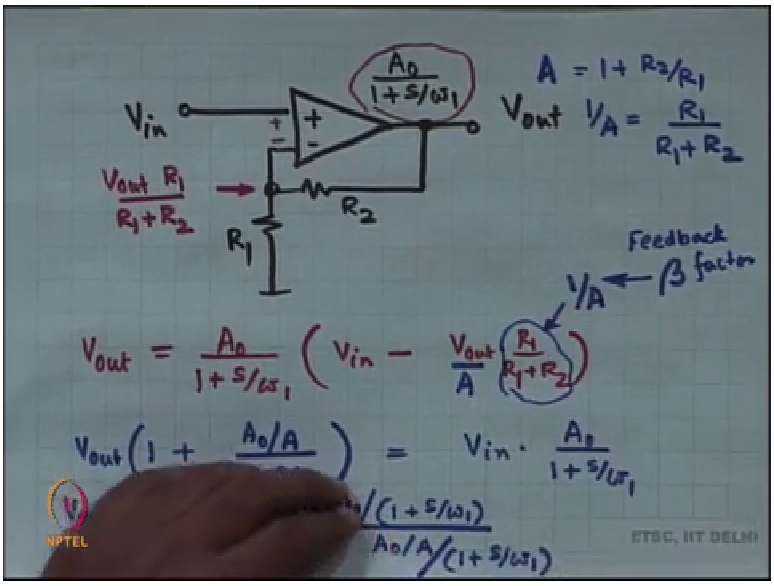

So, in this case beta is just 1 by A; whereas, in the other circuit, beta is 1 by 1 A, ok.

So, in the non-inverting amplifier the feedback factor is just 1 by A. In the inverting amplifier the feedback factor is 1 by 1 plus A, alright. So, slight change, and if you say that the feedback factor is just 1 by A in the non-inverting amplifier. Then, it follows right it straight away follows that, you know, this bandwidth is just beta times omega naught, whatever to beta is right. Earlier we were calling it omega naught by A now I am calling it omega naught times beta where beta is the feedback factor, alright. So, this is the logic, whatever your amplifier structure is, you have to figure out what is the feedback factor. And feedback factor times the unity gain bandwidth will give you the overall bandwidth of that circuit, alright.

So, with this we are going to. So now, you understand why omega not is so important, ok. And not this corner frequency. This corner frequency is of no value. This one has all the value, omega naught has all the value, ok. So, given that we have completed our discussion on amplifiers, we have also completed our discussion on compensation. Frequency response of the amplifiers, how to design the Op-Amp; lot of times after this whole course if you are asked draw an Op-Amp, will you be able to draw an Op-Amp? Lot of people end up not drawing Op-Amps at all.

So, I hope this course is not going to leave you in confusion about what does an Op-Amp finally look like. So, an Op-Amp is finally going to incorporate all these small elements that we have learnt. We have learnt it in bits and pieces. We started from the common source amplifier right. So, then from the common source amplifier, we built up into a differential amplifier. So, the Op-Amp should have a differential input stage, because there are 2 inputs.

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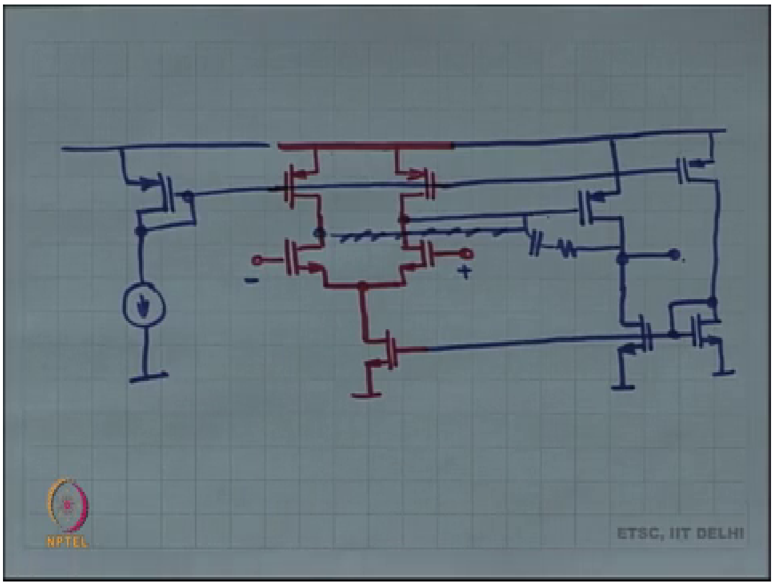

So, you are going to have 2 inputs ok, and differential input stage means that, at the source you need a tale current. You have also learnt about current sources. So, how does a tale current source look like? It is going to look like a MOSFET.

Fine, then lot of people say, that let us place resistors over here. No, as soon as you place resisters, the A times gain of the Op-Amp is going to become very limited very, very limited. So, you do not want to place resisters at all, you want to place an active load,. So, here comes here starts the variation. This part is certain, this is absolutely there. You can not avoid this part right. If you say draw an Op-Amp and you do not draw this part, then you are absolutely wrong, ok. This has to be there then; on top of this you are going to put a load.

What is the load going to look like? If you have an inverse input then the load is going to be p mos, ok. Where is gain? What this, what these gates are doing is left for the future right now. Now for example, these gates to could be hanging connected to some bias voltage right. It could be self-biased for example; this could have been arranged as a current mirror right. All kinds of things could have been done with these gates let us not draw it right now. That there are some p moses to do the load is what is important.

Now, if you are going to do a single ended Op-Amp as a post to a differential ended Op-Amp, then you are going to take only one output as a post to 2 ok. A lot of people take 2 outputs, and then in the second stage have another differential amplifier, that is also perfect. That is also perfectly fine, that will just give you larger common mode rejection ratio. So, it all this is all the engineering right. Lot of these options are there. One option is that you take just one output from the first stage and create a second stage.

Another option is that you take both the outputs from the first stage and make another differential amplifier as the second stage, right. Maybe this time you can have a pmos differential amplifier. It all depends right you can have a p mos differential amplifier; you can have an n mos differential amplifier. You can take just one output, and have just one common source structure, right all these possibilities are there. Now you build a second stage, and then you take the output from the second stage.

So, this is what the Op-Amp should look like, right. So, I will just give you an example, let us forget about the differential, let us just make a second stage. And for variety I make it a pmos second stage, with an nmos active load ok. This is your output. How will you put the plus minus signs? Well, if this is the output, then this is this will be minus right. And that means, this node has to be plus, because there is one more inversion. Then after this you have to compensate, because now you have made a 2 stage Op-Amp.

So, you better compensate right. And then you need to have biasing for this current source. You also need to bias these 2; these 2 are also like current sources right. So, maybe you can mirror all of these together. So, from one reference current, I mirror create the p mos biased voltages, create the n mos biased voltages. And of course, you have to ratio all of these, right. So, so that this takes double the current as these. These are all the items then, what else do? You have to do you have to make this reference current source. How will you make the reference current source?

We had discussed constant g m biasing right. So, all of these little little things that we have studied, all of these have to be put together into the Op-Amp, right? And the Op-Amp has to be designed to some specification, alright? Power, bandwidth all of these are going to be part of your specification, alright. Now, any other important things that you are forgetting over here? Sometimes you want better current mirrors in which case you are going to make cascade current mirrors, right. All of these little things that we have studied; they are all going to be put together in this overall design of the Op-Amp.

So, with this we are going to conclude the study of the Op-Amps, right. And we are going to move to the next topic in the next lecture, we are going to start talking about power amplifiers. And we are also going to start talking about voltage regulators,. So, thank you very much, we will meet in the next class.