Analog Integrated Circuit Design
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Lecture - 17
Feed forward Compensated Opamp

Hello and welcome to lecture seventeen of analog integrated circuit design. Transfer function of the three stage, feed forward, compensated opamp and a look at the stability criterion relevant to those things.

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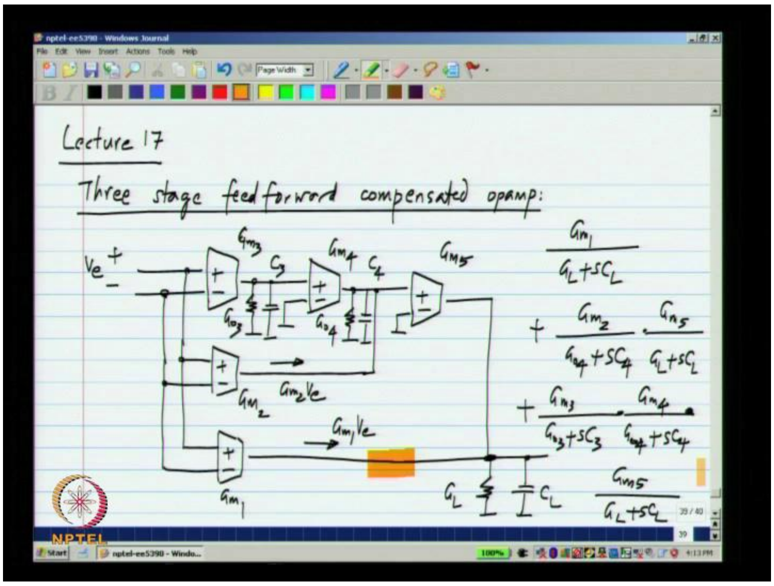

I will think of G m 1 as the single stage opamp that I started with and I will represent all of the output conductance of the G m 1 and this trans conductor. Also any external load that may be connected, as the single conductance G l and also all the capacitances at that load into the single load capacitance C l. Let me call this with different numbers Gm 2, Gm 3, Gm 4, Gm 5 and each will have some output conductance Go 3.

There will be a capacitance here for integration, that is C 3 and here I will represent this as Go 4. It represents the output conductance of Gm 4 as well as Gm 2. They are in parallel and similarly I will just call this C 4. So, this is the three stage, feed forward, compensated opamp. I am not going to write the expressions for the transfer function because it looks quite complicated and ugly although it can be done.

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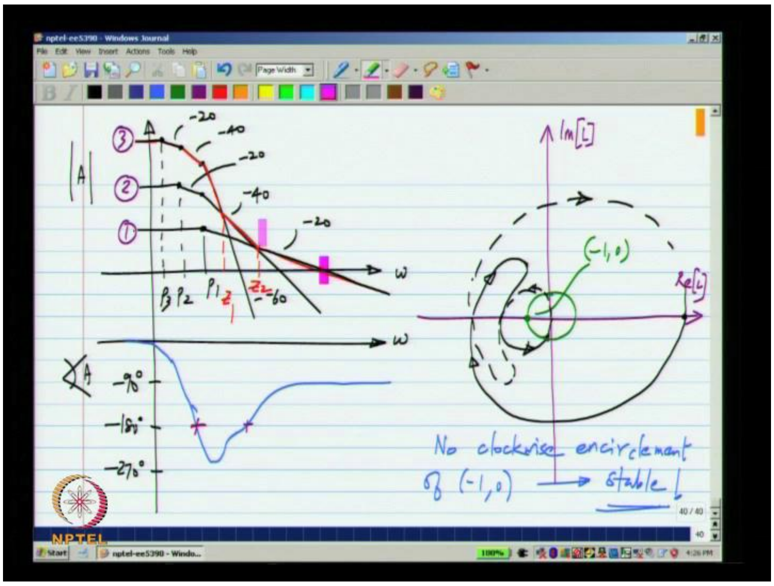

What I want to do is to draw the, first draw the bode magnitude in phase plots. Magnitude of A. So, A of course, is nothing, but the output of the Opamp divided by the input of the Opamp. This is what we have been using the whole time versus omega and also the angle of A versus omega. So, how do we go about doing this without writing the expression? It is possible because, first of all just like in the two stage, feed forward, compensated Opamp, first we see that we have a load Gl in parallel with Cl.

To that we have 2 current contributions. 1 from this, 1 from Gm 5 and the contribution from Gm five can in turn be considered as the sum of the contribution from Gm 2 and whatever is coming from Gm 4. They go into Go 4 and C 4. Now, the contribution from Gm 1 will be of the form Gm 1 by Gl plus SCl that is the output voltage due to Gm 1. That is very clear. Gm 1 times, Ve flows here.

The contribution due to Gm 2 will be Gm 2 Ve flows here. That goes into that load and that gets converted into current through Gm 5 and that goes into the final load. So, we will have Gm 2 by Go 4 plus SC 4. That is the transfer function from Ve to this voltage times Gm 5 by Gl plus SCl. That is the overall transfer function and finally, Ve has a transfer function Go 3 plus SC 3 times, transfer function from here to there which is Gm 4 by Go 4 plus SC 4 times the transfer function from here to there which is Gm 5 by Gl plus SCl.

Now, I just wrote down the transfer functions without going through the analysis. I am assuming you are familiar enough with Laplace transforms and basic circuit analyses to be able to do this. If not, please go ahead and refresh those things because this is quite easy. You have a current flowing into a parallel combination of a conductance and capacitance and this is the kind of transfer function you get.

So, finally when you add up all these things you see that you will have 3 poles. 1 due to this times Gl plus SCl, another due to this times Go 4 plus SC 4 and another due to this times Go 3 plus SC 3. Also when you add up all these things, you will multiply Gm with the second order term, Gm to Gm 5 with the first order term and Gm 5 will remain as it is here because in the denominator you have all 3 terms.

So, finally you will end up with an expression which has 3 poles and 2 zeroes. That is pretty clear without my having to evaluate specific numbers and so on. So, in this particular case we will have A naught 1 plus S by Z 1, 1 plus S by Z 2 and 1 plus S by P 1, 1 plus S by P 2, 1 plus S by P 3. The zeroes will be at minus Z 1 and minus Z 2. Poles will be at minus P 1, minus P 2, minus P 3. All these are positive numbers and all poles and zeroes will be in the left half S plane. I am not interested in evaluating the exact numbers, but I just want to show the nature of stability criteria when you have such a function in a feedback loop.

As usual we assume that this opamp is in unity feedback. So, that it offers itself as the loop gain. Now, to again derive the nature of this I will show it as the sum of these 3 terms, this one, that one and that one. That is what we did for the two stage, feed forward, compensated opamp. The very first term will have a low DC gain and then a 20 dB per decade roll off. Now, the next term here, this one will have a higher DC gain because it is a product of DC gain of 2 stages, but eventually it will have a 40 dB per decade roll off.

So, it will have let us say higher DC gain which is somewhere over here. Let us assume that this let me call it P1, P2 is lower than that. That is my assumption. It starts off with the 20 dB per decade roll off and then it has minus 40 dB per decade roll off. Here it is minus 20. Finally, this last term over here will have even higher DC gain. It is a product of the DC gain of 3 stages Gm 3 by Go 3, Gm 4 by Go four, times Gm 5 by Gl and it will have 3 poles.

I will assume that P3 is even lower. It starts from a high value, drops by minus 20 dB per decade, drops further by minus 40 dB per decade and then drops at minus 60 dB per decade. Here it is minus 20. So, these are all the slopes. Now, we have to add up all these things again. We just make use of the fact that this is in a log scale and we are not particularly interested in getting high accuracy around the points where the magnitudes are similar.

So, we simply follow the higher one. So, now let me mark these things. This is just one path from input to output, 1 amplifier stage. This is the cascade of 2 stages. This is the cascade of 3 stages. From here, from very low frequencies up to somewhere around here, the cascade of 3 stages will dominate. So, we will have something like that. We will have the 3 poles in the transfer function and at this point, the cascade of 2 stages will dominate the gain magnitude.

So, we will have a gain magnitude like that and clearly to shift from here to that 1, we have to have a 0 at that point and similarly beyond this point onwards the single stage will dominate and there will be a 0 there which is Z 2. So, we can easily understand how the 3 poles and the 2 zeroes come about and also you see that at very high frequencies it is the single stage that is dominating.

That again makes intuitive sense because what happens at very high frequencies as you know capacitors becomes short circuits. So, if you look at this path hardly any voltage appears across these capacitors. So, nothing is contributed by Gm 5. Similarly if you look at this path hardly any voltage exists across C3 and C4. So, nothing else gets contributed by Gm 5. Only current contribution is from Gm 1 which goes into this load. So, the red curve represents the magnitude of A of S.

Now, we also know that all the poles and zeros are in the left half plane. If you are doubtful, please write down the expressions and verify that. About the phase response the way I have drawn it. First, I have the 3 poles after there that this 0 and that 0. Now, the 3 poles will give a phase shift that will reach minus 270 degrees. For instance, if we had 3 poles and nothing else. So, basically we would have something, something like that and it will stay at minus 270, but of course, we have zeros Z1 and Z2.

So, what happens is it goes perhaps close to 270, but because of 0 there is a phase lead and then it comes back up and because of Z2 there is further phase lead and then it comes back up and eventually these 3 will give a phase log of minus 270 degrees. These 2 will give a phase lead of plus 180 degree and phase eventually reaches minus 90 degrees.

Now, this is not meant to be very accurate, but qualitatively this is what it does. So, this is the angle of the phase. Now, my first question is… So, many times instability on negative feedback systems is explained as assigned around the loop you have a 180 degrees phase shift and that keeps getting successively amplified. Normally what is said is that you have some A in feedback loop.

If you have 180 degrees phase shift, what is said is the same signal gets inverted through the 180 degree phase shift and gets further inverted through this minus sign. So, it comes back in phase and then gets amplified and that is why in every circulation of the loop you get further amplification and you have instability.

Now, if you look at this particular plot, when the phase shift is minus 180 degrees here and you clearly see that the gain magnitude is much more than 1. So, does it mean that this amplifier is unstable? So, this happens. In fact, not at 1 place, but 2 places. So, here and here the phase shift happens to be minus 180 degrees and the way I have drawn it the gain magnitude is definitely more than 1. Now, if you place this in unity negative feedback, is it going to be unstable?

The conventional reasoning seems to imply that although, that reasoning turns out to be incorrect and for proper analyses we have to go back to the latest plot. Let me draw the micro spot of this. Imagine the part of loop gain, real part of loop gain as usual the opamp gain itself is loop gain because we assume unity feedback. Now, at very low frequencies we start from a very high value of DC gain given by somewhere around here.

So, that let say is somewhere over there and then as you proceed at to the higher frequencies the loop gain magnitude keeps on reducing. So, that means, that the curve will keep on finagling inwards and also the phase shift is always negative and then it keeps on increasing all over down to almost minus 270 degree phase lag. So, it will keep coming closer to the origin. In fact it goes beyond minus 180 degrees phase lag that it can even go close to 270 degrees phase lag. What happens after that? The magnitude is continuously decreasing.

So, it will go closer to the origin, but the phase lead from the 0 starts coming into the picture. So, it will double back like that and the way I have drawn this bode plot, the unity gain crossing there that is where it will enter the unit circle. In fact, the wave I have drawn this phase shift is almost minus 90 degree when it enters the unit circle.

It is something like that. That is what it does and the unit circle it is here. The critical point of course is this minus 1, 0. This is one-half of the micro spot. The other half will be the mirror image. Let me put the arrows so that you can figure out if there is encirclement or not. Now, here what we are worried about is encircling the critical point of minus 1, 0 in the clock wise direction. You see that, this goes around like that and comes back like that. So, there is really no encirclement in the clock wise direction at all because you go and then come back and then you go around it in the counter clock wise direction and then you double back again. So, there is really no encirclement of minus 1, 0.

This means that this system is stable right? In fact, in this case there is no encirclement at all. So, this clearly says that the system is stable and micros criterion is something that is gregariously derived. Basically, the number of encirclements equals the number of poles in the right half plane assuming that there were no poles in the right half in the original open loop opamp.

So, the micros criterion which is a regress stability criterion says that this system is stable, but some sort of intuition based on this minus 180 degrees phase shift and again being more than 1 seems to say it is unstable. So, which is say unstable of course, the micros criterion is correct. It is not true that if the phase shift is minus 180 degree and the magnitude is greater than 1 the system is unstable. In this is the perfect example of a case where it is definitely stable.

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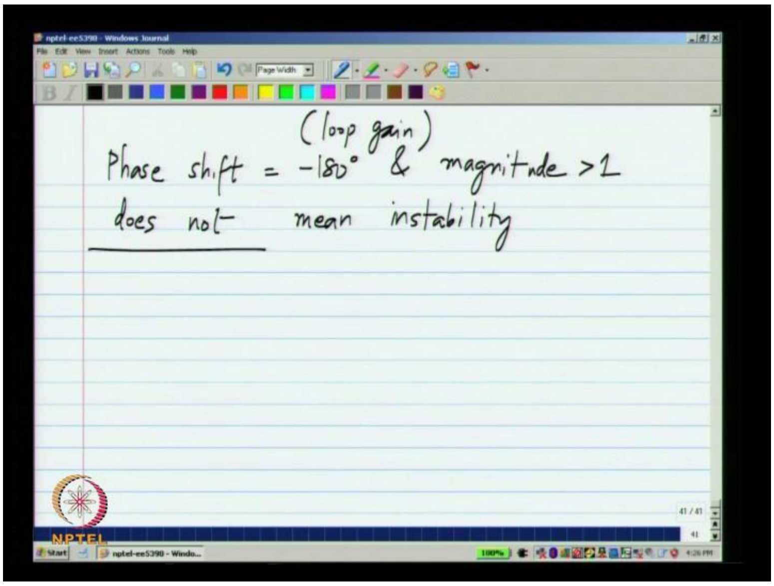

Of course, we are talking about phase shift and magnitude of the loop gain. What matters is whether the micros spot encircle minus 1, 0 or not.

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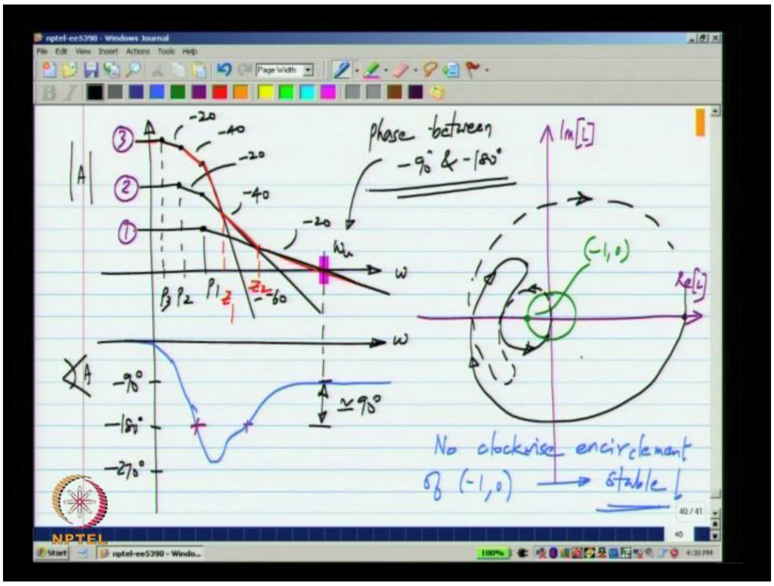

Now, of course, it is very inconvenient to keep drawing the micros spot every time. So, as before we like to articulate our stability criterion in terms of the bode plot. We do know that where the micros plot enters the unit circle is where the magnitude of the bode plot crosses unity, here right? That is our unity gain frequency and the phase angle at that gives you the direction from which the micros plot enters the unit circle. So, if the micro spot enters the unit circle somewhere in the third quadrant, so that means that you are safe.

So, the mirror image you can imagine and it will not encircle the minus 1, 0 point. We will assume some more things that first of all the bode plot cuts the unity magnitude at only 1 point if it goes up and down above and below the unity, the things could be complicated, but that usually does not occur for real systems. So, we will not worry about those things. So, if it crosses unity at only at 1 point so then, it enters the unit circle and never leaves there.

The angle of the loop gain will tell you the directions from which it entered. If this angle is between minus 90 and minus 180 degrees you are safe. So, essentially what should happen is that around the unity gain frequency you should have a phase between minus 90 and minus 180 degrees. In other words we know that pole causes the phase lag of minus 90 degrees and each 0 causes a phase lead of minus 90 degrees. So, you can have any number of poles and zeroes before the unity gain frequency, but the number of poles minus number of 0 should be 1 then the net effect is that of a single pole and we know that the single pole system will be stable.

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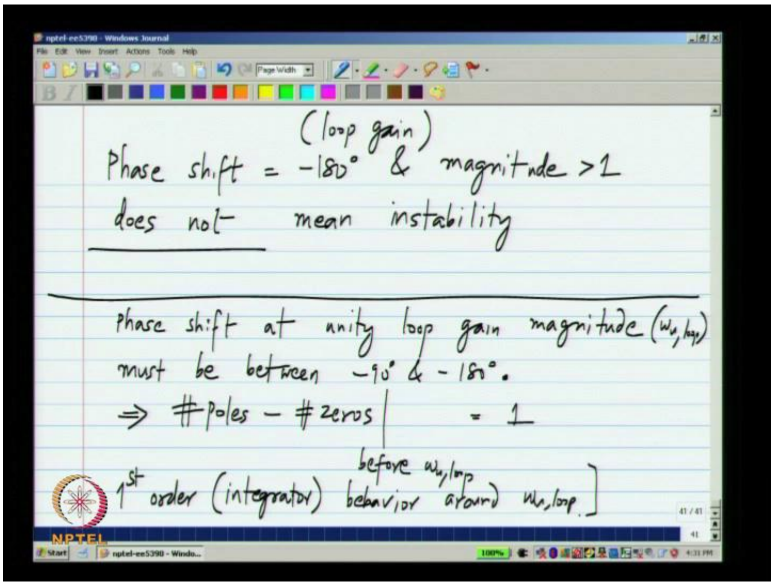

So, that means that essentially when you reach the unity gain frequency the bode magnitude plot should look more or less like that of a first order system. That is minus 20 dB per decade and that is what is shown here because you could have many poles and zeroes before, but the effect of poles are cancelled by the effect of zeroes. So, finally if you have let us say 3 poles and 2 zeroes as shown here. After this point it behaves more or less like a first order system or like an integrator. So, earlier on in the course we took the integrator as a model for a negative feedback system. Now, we see that in every case around the unity gain frequency which is the crucial area, the loop gain will be like that of an integrator.

The loop gain function will be an integration function. As usual you can ascertain the stability margin using the phase margin. The way I have drawn it, the phase margin here is almost 90 degrees, but that does not have to be the case. I will show a couple of examples where it can be less than 90 degrees, but still be stable. Now, when SI minus 90 minus 180, it could also be a phase lag of less than 90 degrees, but that is not likely to happen. If this is the case, it behaves more or less like a first order system around the unity loop gain frequency. This in a sense is like the criteria for stability. We can see that it also measure well with our earlier criterion. What did we say? Any poles should be well beyond the unity gain; loop gain frequency.

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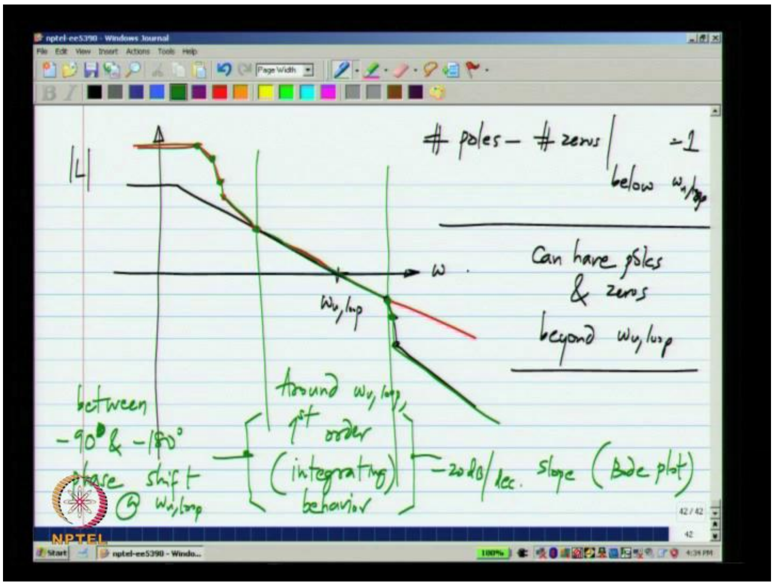

So, earlier we said that we could have a loop gain like this and then you could have parasitic poles and zeroes here. It will be stable. Now, what we are saying is you could have zeroes and things here and it will be stable. So, what does it finally mean? You could have poles and zeroes anywhere so, the number of poles minus number of zeroes below omega u loop should be 1.

There is no restriction on the number of poles itself or the number of zeroes, but the difference should be 1. Basically you should have the effect of only 1 pole around the unity loop gain frequency. This is by the way is the magnitude of the loop gain versus omega and you can also have… This is also possible. So, you could have bode magnitude plot which looks something like that which combines both. You have 3 poles 2 zeroes before the unit loop gain frequency and after that you have a bunch of poles and zeroes.

This will also be stable. So, what matters is that around omega u loop you have a first order or integrating behavior and a first order behavior means a minus 20 dB per decade slope in the bode plot. Remember bode plot itself is an approximate plot with the straight line segments instead of the complicated curves they follow, if the poles are close to each other, or poles and zeroes are close to each other you will not have straight lines, it will be some smooth curve but in the bode plot sense you should have a minus 20 dB per decade slope and in the phase plot.

So, the same thing implies the phase lag of somewhere between minus 90 degrees and minus 180 degrees. We will not assume pathological cases where loop gain goes below unity and comes back up to unity or close to unity and so on. If that is not the case you can ascertain stability just by looking at the bode plots, just by making sure that you have essentially first ordered behavior around unity loop gain frequency. It is important to keep in mind that if the phase shift is minus 180 degrees and the magnitude is more than 1, the system is not necessarily constrained. You have to look at the phase shift when the magnitude is 1. Not start some other frequency. Now, can this be unstable? It is certainly possible. Let me copy over this plot.

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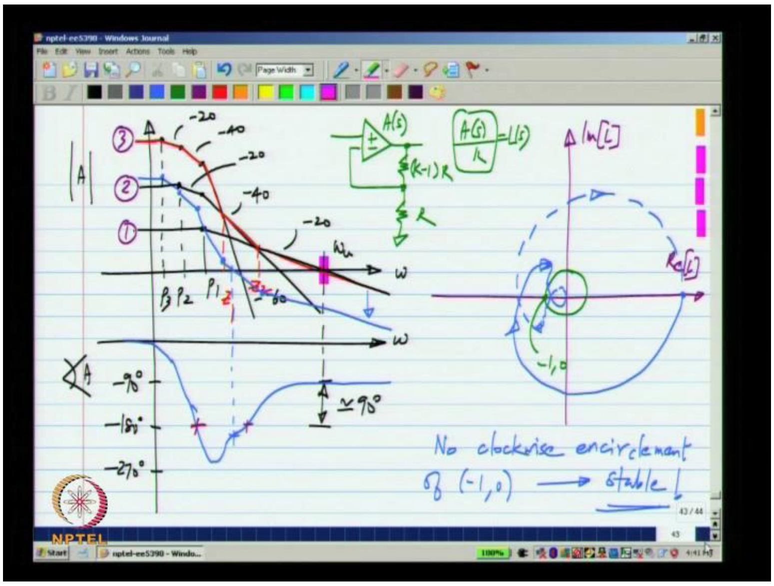

So, first of all let me assume that this is the gain of the opamp. That is the gain is given by the red curve and if the opamp is in unity feedback, this is the loop gain and that is what we have evaluated so far. So, let me say that I have the same opamp and I try to make an amplifier of some gain K. So, if the opamp has the transfer function A of S then loop gain will be A of S by K.

So, what will be the loop gain of such a loop? First of all, you have A of S by K has the same phase shift as A of S. So, the phase plot does not change. The magnitude of the loop gain is 1 by K times the magnitude of A of S. So, that means, simply shifting the magnitude plot by some amount downwards. Let me draw it over here. All I am doing is taking the red curve and shifting it downwards by some amount.

So, that is what I have. So, this is simply shifted downwards and the phase plot remains the same. Now, when this crosses unity I have the phase angle which is more negative then minus 180 degrees. What will the micro plot of this look like? It looks like the original plot has been kind of compressed inwards. So, it does that. It does that. Qualitatively it is the same, it goes beyond minus 180 degrees, but when it enters the… wait I will redraw this one because it is too confusing with the 2 curves. This is the unit circle, imaginary versus real part of loop gain.

The new micros plot, qualitatively similar behavior it spirals inwards and so on and then it goes to the phase shift beyond minus 180 degrees then it comes, but when it enters the unit circle that is here the phase shift is beyond 180. So, it does that and then it comes all the way to 90 and if I look at the mirror image of that 1 that is what it will have. Now, in this case what happens is that we have gone around the critical point which is here, minus 1, 0 once in the clock wise direction.

So, we have gone around it like this and this small loop is nothing. It does not enclose minus 1, 0. So, it does not cancel or add to the number of loops. So, it is like making an extra circle there and then it comes back here. So, effectively we have gone around once around the minus 1, 0. So, now, this is indeed unstable. So, such a system is known as conditionally stable system. When you have multiple poles and zeros before the unity loop gain frequency in general, it is a conditionally stable system.

Because, if you have an Opamp with many poles and zeroes before the unity loop gain frequency, by increasing K, that is by reducing the feedback fraction, you can lower the curve. What happens is, as a result the frequency at which the loop gain crosses unity, the unity loop gain frequency could be such that the phase angle there is more negative than minus 180 degrees. In that case you will have the encirclement of the minus 1, 0 in the profile direction and you will have poles in the right half time in the close loop.

((Refer Time: 32:00))So, it will be unstable. So, one of the things to keep in mind is that when you increase the gain or when you reduce the feedback fraction, the feed forward, compensated opamp can become unstable. We will contrast this with the Miller compensated opamp shortly, with this, something to keep in mind. But the stability criteria when you have multiple poles and zeros before the unity loop gain frequency should be clear by now. So, the stability criterion is that if you have n p poles before the unity loop gain frequency you should also n p minus 1 zeroes. So, that the phase lag due to the n p poles is cancelled to a large extent.

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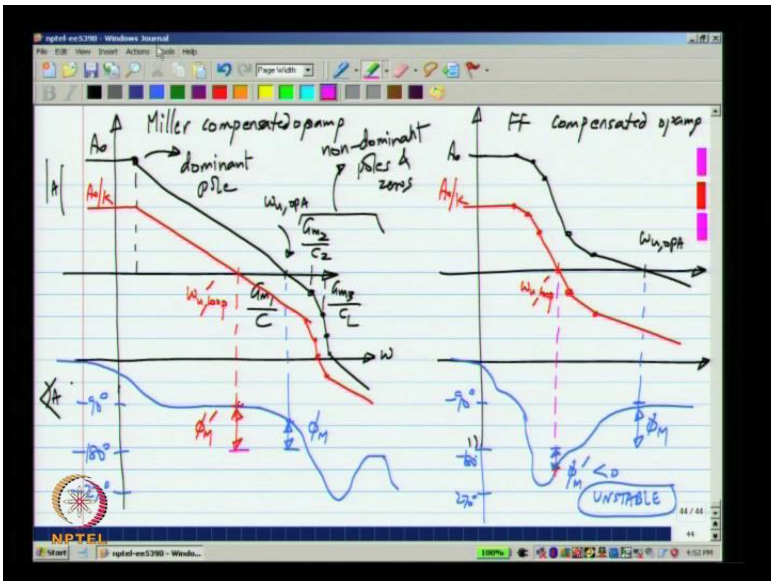

So, the 3 stage, feed forward opamp can be stable and the stability criterion we just discussed. Let us consider making a Miller compensated opamp and the feed forward compensated opamp. Now, we did not evaluate the 3 stage, Miller compensated, opamp frequency response completely, but we know that we want to make an integrator. So, bode magnitude plot will be something like that, but because of all the additional loops this is Gm1 by Cl using the terminology that we have, sorry Gm1 by C and then we will have ((Refer Time: 34:00)) we will have the non dominant poles and we evaluated them in the previous lecture. 1 of them is Gm2 by C2.

That is the unity gain frequency of the inner opamp and the other one is Gm3 by Cl which is the unity gain frequency of the inner most pamp. These are very crude approximations, but they work for now and there could also be some zeroes. But the point is, we will place all of these things beyond the unity gain frequency of the opamp. These are called non dominant poles and zeroes.

There is a single pole before the unity gain frequency and that is called the dominant pole. Now, all the non dominant poles and zeroes are placed beyond the unity gain frequency of the opamp. This is assuming that we will put the opamp in unity feedback. That is we will make a circuit like this. In this case the gain of the opamp itself is the loop gain and what does the phase shift do? I will draw this in blue.

So, it starts from 0 and close to minus 90 due to the dominant pole and it stays at minus 90 over a wide frequency range and after that depending on the number of poles and zeros it could go to some high value and then come back due to the zeros and go further down if it is right half plane 0 and so on. I will not worry about the details. I will just show that at the unity gain frequency the phase lag is less than minus 180 degrees. Now, the feed forward, compensated opamp we just evaluated that. Let us say we will compare it for the same DC gain. Does something like that and this is the unity gain frequency of the opamp and again assuming the unity feedback configuration such as this one. This is the loop gain.

The phase as we saw earlier it could go close to minus 270 and then finally, come back up to minus 90 and here I will assume it to be close to minus 90. It does not have to be exactly so. There will be some phase margin. Now, let us say that instead of the unity gain amplifier we make an amplifier of gain K. This is not very clear here, but I think you understand what I mean by an amplifier of gain K. I have resistive divider which divides the voltage by a factor of K.

What is the loop gain in this case? Whatever the gain of the opamp is A of S divided by K and as we discussed earlier A of S by K has the same phase as A of S, but a magnitude that is smaller by a factor of K. Now, with the Miller compensated opamp, what happens is that let us say goes down by a factor of K which is like that. The poles and zeroes remain exactly where they are. It does something like that and phase is exactly the same and this is the new unity loop gain frequency and the DC loop gain is A naught by K. What happens to the feed forward opamp again? The DC loop gain is A naught by K and this is the new unity loop gain frequency.

Now, what do you think of this stability of the Miller compensated opamp when you put it in amplifier of the gain K? Now, if we have designed the miller compensated opamp so that the unity gain amplifier is stable. That is this curve has sufficient phase margin. You can see that when you have a curve like this, first of all the magnitude draws monotonically well beyond the unity gain frequency then the phase also drops monotonically.

So, when I go from the black curve to that red curve and look at the phase shift at the new unity loop gain frequency. In fact, it is going to have less phase lag. If my original phase margin in the unity gain frequency was that much, the new phase margin when I make an amplifier of gain K is that much Phi m prime. Phi m prime is the phase margin when I make an amplifier gain of K. I can clearly see that Phi m prime is more than Phi m.

In fact, the stability margin for the amplifier of gain K is better than the stability margin of gain for the amplifier of gain 1. But that is not the case with the feed forward amplifier right? So, originally I have this phase margin which was quite nice. Now, I have a negative phase margin. That is I do not have the phase margin at all, it is in fact, unstable.

So, what we learn from this, if you design a Miller compensated opamp for unity gain operation that is you adjust it so that at the unity gain frequency of the opamp you have 20 dB per decade roll off and all the non dominant poles and zeroes come beyond that. Then we can also guarantee that for any higher gain than unity the opamp amplifier will be stable. That is very good thing.

So, in fact, K equals 1. That is the unity gain, is the worst case for a Miller compensated opamp. When you see opamp data sheets you will see terms like unity gain compensated so that means, that when you make an amplifier of gain equal to 1, the amplifier will be stable. It also guarantees that if you make of amplifiers of any other gains higher than 1 it will be definitely stable as wel1. That is the good thing.

That is not so with the feed forward compensated opamp. In a feed forward compensated opamp, when you try to make on amplifier of gain more than 1, it is not necessarily stable. That is very obvious from this picture. When you drop down the magnitude plot originally the region where the plot crossed unity, that is, the unity gain frequency there was the 20 dB per decade slope.

But below that we have the region where the slope is more negative than 20 dB per decade. Here we have 60 dB per decade. We see that the right curve is crossing unity when the slope is minus 60 dB per decade. This violates a stability criterion and the system is unstable. So, if you have a feed forward compensated opamp that works well for a gain of 1, it does not mean that it will work well for a gain that is greater than 1.

So, feed forward compensated opamp necessarily has to be designed for whatever gain you want. Whereas with the Miller compensated opamp you are safe if you design for a gain of 1 it is going to be stable for any gain greater than 1 and we are talking about amplifier so obviously the gain will be either 1 or more. So, the Miller compensated opamp is easier to design for a general purpose application than a feed forward compensated opamp.

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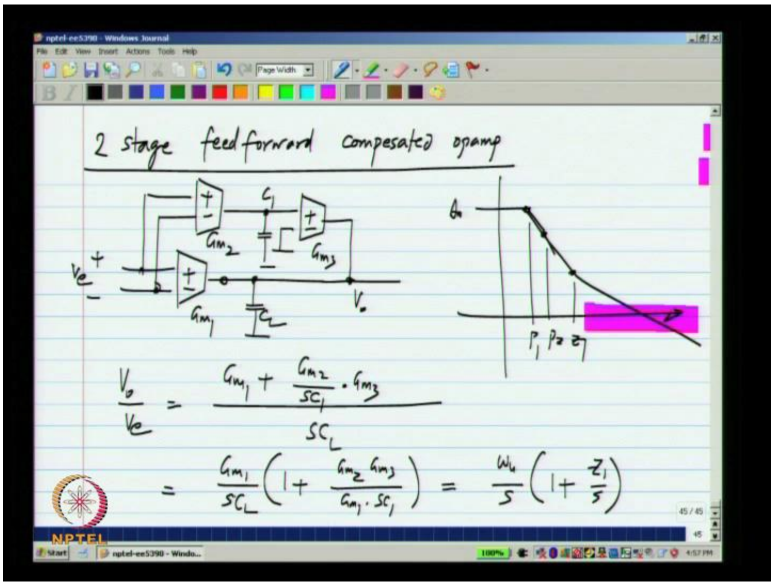

So, that is about the stability criteria. In short you can have many poles and zeroes. That I have repeated many times, but what matters is at the unity gain frequency you have the effect of a single pole. Let us consider a 2 stage, feed forward, compensated opamp. Now, we know that the bode magnitude plot does something like that. There is some finite DC gain A naught and there is pole P 1. There is another pole P2 and there is a 0 Z1. Then after that you have a 20 d b per decade slope.

Now, for stability what matters is this region. The fact that you have finite DC gain does not matter so much. This I have articulated before as well. Now, because if you have the imagine micros plot, the stability relates to what happens when the micros plots enters the unit circle not elsewhere in the plot. So, more or less we can safely ascertain stability by characterizing this part accurately and ignoring this part and I also earlier said that you can assume that DC gain is infinite while looking at the stability.

That is what we will do here. We will assume that these conductances are not there. This is an unrealistic case in that, first of all we made the 2 stage feed forward compensated opamp only because the conductance is finite and we have a finite DC gain, but here we will make this approximation only for analyzing stability because it makes life a lot easier.

What will be the transfer function of an opamp like this? Vo will be the total current going into the capacitor divided by the SCL which is Gm 1 plus Gm 2 by S C 1. That is the voltage over there times Gm 3 divided by SCL. Which can be written as, which in turn can be written as the intended unity gain which is Gm 1 by Cl because recall that this is the single stage opamp that we started with. That is the unity gain frequency that you are trying to realize and this is in a non standard form.

S is in the denominator and this rest of that it is the 0, but I will leave it like that. Omega u by S times 1 plus Z1 by S. So, this is Vo by Ve and we will use this to analyze the stability of the 2 stage feed forward compensated opamp and draw conclusions about how close Z1 can be to the unity gain frequency.

Thank you. See you again in the next lecture.