Analog Integrated Circuit Design
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Lecture - 16
Op amp Realization- Feed forward Compensated Op amp

Welcome to lecture 16 of analog integrated circuit design, we are in the process of designing Op amps at the level of control sources or transconductors and improving their performance. In particular, we want to get higher and higher DC gains, we want to figure out how to make this Op amps with higher DC gain. Of course, maintaining satiability of the feedback loops, we already saw some techniques which there was a two stage and three stage similar compensated Op amps. Now, we will look another techniques to increase a DC gain starting from the original integrator topology.

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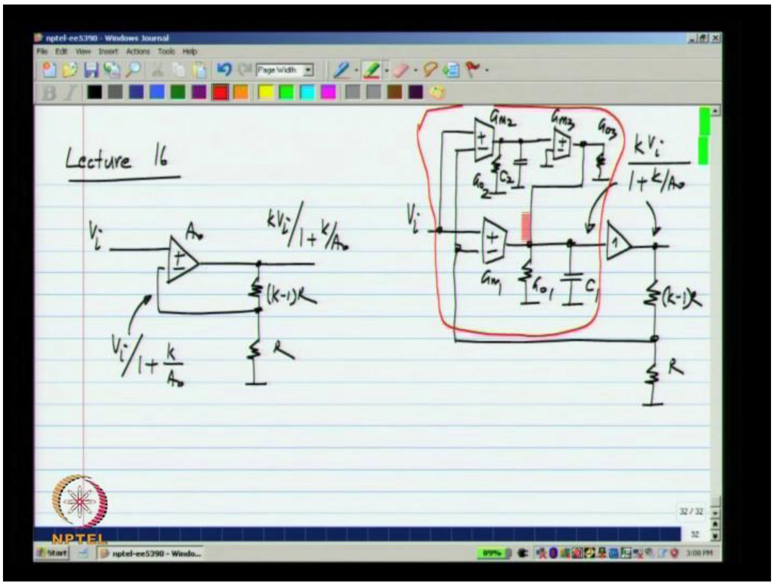

I will use the standard Op amp amplifier as an example, if I apply constant input V i and the ratio of resistor k minus 1, the output is supposed to be k V i. What we really get is k V i by 1 plus k divided by A naught, where A naught is the DC gain of the Op amps and the voltage here should have been V i itself. That is the two voltages being compared by the Op amps should be the same, after it reaches steady state, but they are not and this voltages is small. Then, V i it is equal to V i by 1 plus k by A naught, it is close to V i, but not exactly equal to V i. Now, let me use the Op amp that being a discussing the simplest Op amp, it has it has transconductor which has an output conductor.

That is loaded by capacitor and just for simplicity I will insert a buffered here, but this is not really necessary letter one, we implement Op amps, we see that it do not always implement the buffer. Now, this we know as a DC gain A naught equals G m 1 by G o 1. So, whatever I describe left side will happen here and voltage here will be slightly smaller than V i. Now, we will try to fix the situation by going back to the idea, the original idea, and the negative feedback what was that first of all in steady state.

What happens that there has to be some current flowing to G o 1, so that there is the certain voltage that is supported here. The actual output voltage turns out to be k V i by 1 plus k by A naught and it is same here and if this voltage as to be this note some current has to be flowing through G o 1. That currents comes out of this transconductor G m 1, now if current has to come out this transconductor. These two voltages have to be different from each other, because after all they were the same the current output of the current conductor would be 0. So, to fix this what we must do a this to provide the current that is flows through to 0, 1 from a different path.

So, transconductor itself does not have to provide a output current, so its input different will be 0 and how much this should the current be, we do not know exactly what it will be. I mean it is not easy calculate because the parameters G n 1 and G o 1 always things varying and what we would like is to for this current, automatically set itself to a value such that the difference between this two points becomes 0. That is exactly what the original negative feedback idea was doing that is you want to control some quantity based on the error between some desire quantity and some a control level quantity.

So, how do we did that we took the difference between the desired and a actual values and we integrated that over time. In this case, they should be a current the integrated quantity the output should be a current, which is relate to the integral of the difference. So, what happens is that after while a for the reach steady state for this current to be steady, the input to the integrated has to be 0, which means this and that will have to be same as each other. This condition what happens is the current that has to through G o 1 will be provided by this path and nothing will provided by G m 1, so it is input difference can be 0.

So, that is the basic principle, now how do we implement this the integrator and the differencing exactly the where we have o to going been all doing it all a along, first of all we have to make an integrator and all. So, the output of that has to be current integrate the difference between this two voltages, what I do is use the transconductor loaded by a capacitor. Let me call this c 1, I will call this c 2 and finally what I want to inject here is the current. So, I take this voltage and converted to a current using another transconductor. So, this is all I have, essentially the block above what I am doing to take the difference between these two integrated convert the integral to a current.

Fitting it to this if everything works perfectly, then the difference between these two voltages has to be 0 in steady state. Also, keep in mind that we said that the circuit below already richest steady state the other controller appears into picture. In reality, both are working simultaneously, what we really mean is that the second circuit this integrator and the transconductor. This signal path operate more slowly compare to this particular circuit this is. So, that essentially what this transconductor here should be measuring is the steady state error between these two and providing compensating current which is related to the integral of that steady state error.

So, this ideas is looks fine and you can see that in steady state there will no current flowing for this capacitor c 2. So, these two voltages will be equal to each other, but of course the catch is that we said this transconductor will have some output conductance which is not 0. Similarly, this transconductor will also happens output conductance which are not 0s. So, we will inactively have that one, so let me call this G m 2 and that will be G m 2, similarly if this is G m 3, it will have its own output conductance G o 3.

So, it is one things to get an idea and the next thing is to a put s down all the non ideal effects that come in well implementing the idea and see if it really works . So, now my Op amps, I can call this entire complicated beast my Op amp because whenever I make the Op amp negative feedback circuit I am going to use the whole thing. I will use this was my original Op amp, but the fix the steady state this signing all of this tuff, but I need all of this stuff. So, I am going to use the whole things, so that is my new Op amp are may not or use the buffer as usual.

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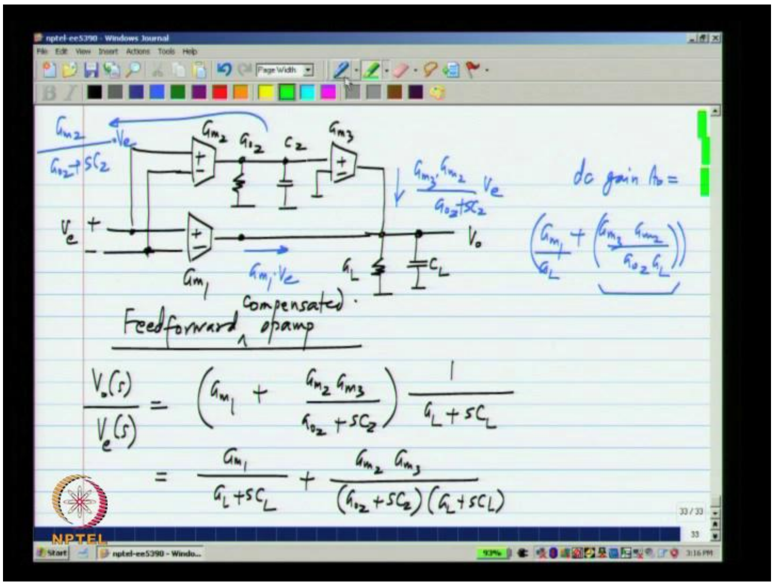

So, if I redraw the Op amp by itself, I have the original part, I have the part, I have added and this will also have some G o 3, this is G m 3 and there could be a c 3 as well this is the input to the Op amp and that is the output of the Op amp. Now, as usual I could use the buffer after this, but I will assume that cannot, but normally in CMOS circuits, V tend, use t although it is very much possible.

Finally, you see that this G o 3 and G o 1 in parallel, it in also be parallel with any load resistance you connect. Similarly, c 3 and c are in parallel and they also be in parallel with any load capacitances that you connect. So, I will combine all these things into a single load conductance G l the load capacitances c l. So, this is my new Op amp and remember our goal was to improve the DC gain, the Op amp. Now, this will have higher DC gain very easily usual by opening the capacitor and what will be the dc gain of this if i apply V e, here the voltage that appear there will be G m 2 by G o times v. The current that flows here will be G m 1 times V e and that current that flows here is G m 3 G m 2 by G o 2 times v.

So, the output voltage at DC will be nothing but G m 1 plus G m 3 G m 2 by G o 2 the whole thing divided by G l and this is the DC gain. Now, it is very easy to see that this was the original DC gain and we added this much. In fact, what we want added is likely to be much more than the original DC gain because it is essentially is the DC gain of two stages. In fact, it is the similar number what you got from the two stage mailer compensated Op amp. The two state mailer compensated Op amps after we implanted all those stages using transconductors at this form it was product of two G m by G o's similarly, here we have that we also have this one added, but G m three by G o two is likely to be a large number.

So, most of the DC gain is provided by this path and where as this provided a modest amount of DC gain, whereas this a performs the function of integration, but its required inside the Op amps the G m one and c l together and this provides the the other path provides the DC gain. So, our idea has work and we have got an Op amp with the higher DC gain, now we also have other capacitor here, which means there could be a more pulse and 0s. We do have to analyses that in c f stabilities this is the DC gain A naught and roughly speaking it is like the DC gain of the cast state of two stages, which is the two stages one top medium and because we have two stages here.

The single stage going from the input to the output of the that is usually known as feed form forward and this is known as a the feed forward Op amp or sometimes feed forward compensated Op amp. Now, the term frequency composition is the term the commonly use to get the h behaviors of integration in the Op amp. I have earlier said that the Op amp has to behavior as integrator at least in some crucial range of frequencies. Whatever you do in the circuits' domain to get that integrating behavior is called frequency compensation we are not use the term often, but that what it is, I will explain later what it means in different contacts as well.

So, in this particular case this transconductor f G m 1 together with c l provides that integrating behavior and that is feeding forwards across the two stages that we get a high DC gain. So, it is called the feed forward Op amp, now the next thing we have to find out is the frequency depended behavior v naught of this area of this. This is what we did for the miler compensated Op amp and other Op amps that we discussed earlier. Again, that is quite easy all I have to do is recognize that the voltage at the output first stage is not nearly G m 2 by G o 2, but G m 2 by G m 2 plus c 2 times v.

We all also have the capacitor, so that voltage will be G m 2 by G o 2 plus c 2 times V e. So, the current output of the G m 3 will be G o 2 plus s e 2, it will have G 2 plus se 2 in the denominator and the current output of the G m 1 will be G l v, the two terms get together. So, we not a phase by transfer to be G m 1 plus G m 2 G m 3 by G o 2 plus s e

2 and this whole thing will divided by the load which is G l plus s c l. So, the gain or the transform function of the Op amp can be expressed as some of Op amp this first order term which. In fact, you recognize this is what we would have with the simple single stage Op amps plus this part due to the two stages that we have across them.

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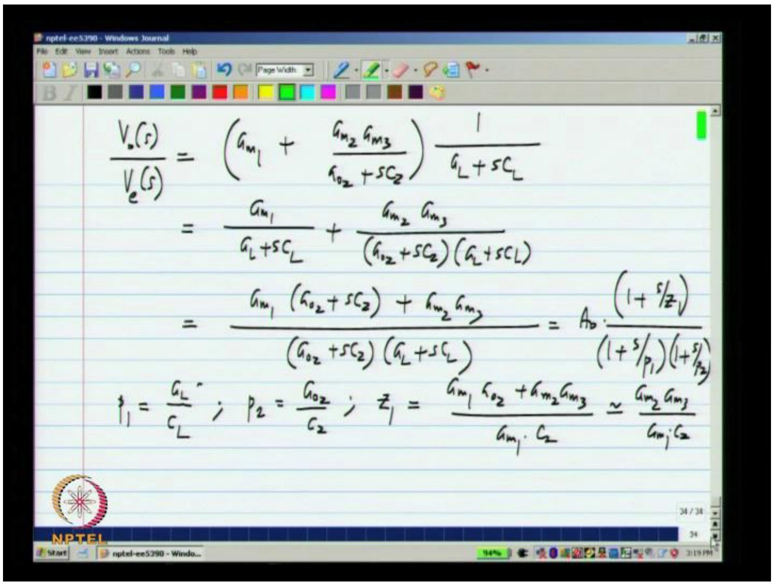

This can also be written as now this you can see of the form some DC gain times 0 divided by times a term containing 0 divided by terms containing two poles. Here, it is the polar is the minus p 1 and p 1 itself will be equal to G l by c l and other pole is the minus p 2 and p 2. It will be equal to G o 2 by c 2 and the 0 G 1 will be at G one G m 2 plus G m 3 divided by G m 1 this G 2 because we expect G o, the output conductance we much smaller than trans conductance's. This can be approximated to G m 2 G m 3 by G m 1 times c 2, this is not s c 2, but nearly c 2. So, we have a transfer function with two poles and a 0, of course the poles are left hand plane and 0 also is in the left hand plane. Now, have to see what the effect of this own the stabilities.

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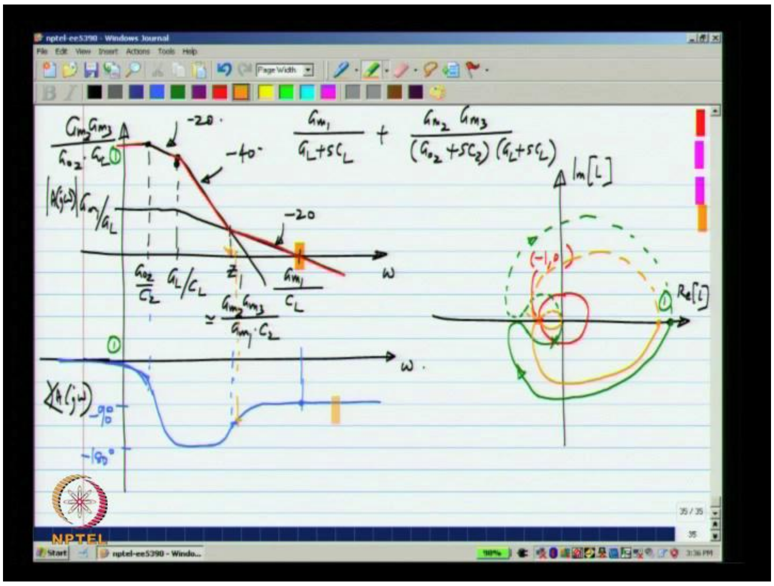

So, we can do that by drawing board and aqua seed plots, let me draw the board a plot here and it is easiest to use the form where we had G m 1 by G l plus s c l plus G m 2 G m 3 by G o 2 plus s c 2 times G l plus s c l. The first of this is a first out of transform function with a DC gain of a G m 1 by G l it has a pole at G l by G l and its rule of out 20 degree decade after that cuts unity gain. If you a recall it will be G m 1 by c l for reasonably large, this DC gains the unity gain frequency will be equal to the DC gain times the pole frequency.

The second term will have a DC gain, which is higher we explain to be higher which is G m 2, G m 3 by G o 2 G l and there will be there will be two poles, one of the poles will be the same value, the other pole for drawing this plot. I will assume to be a lower frequency this is at G o 2 by c 2 that is pole corresponding to that term. So, it rolls up 20 degree per decade and after that I rolls up a minus 40 degree per decade, this is the magnitude of the gain off the Op amp. As I mentioned before, if the Op amp is the unity feedback the Op amps gains itself is the low gain and we can access stability of a unity feedback amplifier. By looking at the gain of the Op amp, what happens when you some this to a remember that is bard a plot is logarithmic plot.

The y axis is log of the magnitude, so when you add up to a different plot like this you can simply approximated by the higher of the two numbers. So, some of the plot of the some of the two we look something like that. Now, this some will this area will both have similar magnitude, but when one is more than the other. You simply follow the higher one to give you the magnitude, so this is the general thing when you have a 2 functions are being added together and especially when you plotted on log scales and you want to plot the some of the two functions. You simply follow the higher valued function, now what happens to the phase first of all drawing for phase our convenient.

The first form that is given by this expression by the way it is also very easy to see where the 0 is in this plot in the magnitude plot. We know that we expect 0, now you see that this slops changed from minus 40 back to minus 20, this part of the curve has minus 20. So, 0 is that that particular frequency we can calculate the value of the zero it was G m two G m three by G m one times c two approximately that is why it is going to be now what happens to the phase plot first of all at low frequency as usual we have a a positive real number.

So, the phase shift phase will be zero that is at some very low frequency let say some where or here. Now, add the first pole G o 2 by c 2, we see that it will have a phase shift of 45 and then it goes out to minus 90 that is the contribution of the first pole. The second pole will add another 45 degrees phase at the frequency and the pole and then the phase shift due to phase that pole also saturates to minus 90. So, after you pass these two poles what happens is the phase would shift to minus 180 degrees, each pole contributes a phase shift of 90 degrees phase lack of phase 90 degrees.

So, the two poles together will contribute a the phase shift, phase of minus 180 degrees or a phase lack phase a 180 degrees, once you go to a frequency that is well beyond both the poles, then you hand the 0 and this zero left hand plan zero. So, that creates the phase lead, so what is do at the frequency of 0, there will be lead of 45 degrees and then phase lead will also saturate to 90 degrees. So, after some frequency, the frequency as the phase become approximately minus 90 degrees, the way I drawn the plot you can see that at the unity gain frequency which is G m 1 by c l.

The phase is close to minus 90 degrees does not have to be, but it will do something this sort that is clear. So, its starts from 0 degrees, when it goes to down minus 180 degrees because of these two poles that comes out to be minus 90 degrees due to this 0. So, this is the phase response of the Op amps, now this magnitude and phase response this bode plot is quite different from the Op amps what we have seen earlier. Also, what we have s discuss in detail what we have say earlier, we have one pole a very low frequencies.

In fact, the Op amp is the integrator that will be 0 frequency and any other poles are 0 should happen after the unity gain frequency of the Op amp that is some point corresponding to this one. Now, what we have two poles before the unity gain frequency that we always have a 0 before the unity gain frequency. So, it is just really stable or not what do you think now to access this, we have to go back to criterion, which is the regresses way of analyzing stability. So, once you understand the micro plot of a system corresponding to this, you can do it from the Bode plot directly.

To understand it properly, we have to go to the micro plot and what is the micros plot, it is the plot of a the loop gain the imaginary part of l verses real part of l as the frequency varying from low to high values from 0 to infinity. So, in this particular case what happens first of all at very low frequencies that is some frequency corresponding to this the loop gain magnitude is very large and the phase shift is 0.

So, that is means we start from some point here do may be market with this 0.1, which corresponds to somewhere here and somewhere. It starts from the positive real access and as you go further the magnitude keeps on lower n, but the phase becomes more negative. There will be more and more phase lack, so this plot this spiracles in word in somewhere finally, it goes all the way down 180 degrees and remember the phase shift phase due to two poles will assemble reach 180 degrees, it will it be exactly one eight degrees our.

So, it cannot touches this negative real access the magnitude of course, it is continuously decreasing. So, it is going on inwards towards the origin and the phase comes back to 90 degrees. So, that means, that this curves will finally, approach the horizon that is horizon means not magnitude is 0 and the phase there is minus 90 degrees. So, that means, that is its approach from the negative imaginary access. So, this will be the micro spot of other free forward Op amps, if it is connected in unity feedback, now this stable or unstable its depend when the units circulate.

Basically, let us say that the unit circulars here on this plot and the micro plot enter circular and then the other half of it will be a mirror image. It will be something like that now you can see that, again there is no in in inclement of this particular point that is this point here is the critical minus 1, 0. You see that the plot kind of goes around it without in circling in the clockwise direction. We saw that then number of clockwise and inclement equal the number right of plane a poles. If the open loops system does not any plane also begin, this in this case there is no inclement, so the system is stable.

System is definitely stable because we can see that a because this only touches the negative real access, it will never actually in circle the minus 1, 0 most adopt is barely touch the negative real access. So, you cannot have plot that goes around the minus 1, 0 ever, but let us say the magnitude response loop straightly different. From this, I will write in different colors. So, let us say it something, this what it says perhaps not mean while again this close goes to negative real access it comes like that. Then, finally it goes to origin that is for sure in the mirror image of that will do that.

Again, there is no encirclement, but you have to see that the plot unit circle, but an angle very close to minus 180 degrees the original green curve enters the in terms the unit circle at this point which this quite far from minus 180 degrees. The orange curve enters the unit circle at a point very close to minus 180 degrees. So, what do you conclude from this the orange curve has very poor phase margin what a m phase margin, after all it is the angular separation between this point minus 1 0 and where the nucleolus pots enters the unit circle. The green curve has a large phase margin which is quite healthy, it will be stable as I said of earlier we derive condition for stability and not only stability margin.

That is good behavior without lot of ringing based on our analyses of system with ideal delay low orders systems like and first orders system and second order system. So, we saw that if you have large phase margin, you will a generally have a several step response does not have ringing. So, in this particular case if you enclose Op amps unity feedback loop and if the Op amps transform function happens to follows f green curve, then there will be no significant ringing. If it follows the orange curve, you aspect they will be a lot of ringing, we will confirm the explicit analysis in this particular case we only have a two poles, this can analyses explicitly.

In general, you can use the phase margin criteria first ability, now we have drawn this plot you see that the 0 appears well before the unity a gain frequency. So, that means that the phase shift at the unity frequencies close to minus 90 degrees. So, In fact, it is closer to the green curve then the orange color, the loop gain corresponding to the orange curve would have been something this sort. It would start from some magnitude, let say it has the same poles and there will be a 0, which may be a little bit before the unity gain frequency of may be and after. So, if the orange curve is what represent the Op amps gain, you can see that the phase shift phase at the unity gain frequency far from minus 90 degrees.

So, this kind of Op amps can be stable, we just have plot to nucleus plot and make sure the phase margin us high, but once you understand this phenomena. You do not have to actually explicitly plot the nucleolus, but it will a certain directly from the Bode plot that he phase margin phase is quite high. We need the nucleus plot because we want to make sure that there is no encirclement of the minus 1, 0 point and there is and we can see that or this point the way drawn the plot, the phase margin is almost 90 degrees.

We just quite healthy, when it possible for it very power margin and become close to stability just like the second order system. This will never become completely unstable, but it can become close to unstable because the nucleus plot can enter the unit circle at a point very close to minus 180 degrees. So, what is the criteria first ability on the Bode plot, first of all we want the relationship at the frequency which is G m 1 by c l to be close to 2 minus 90 degrees. Now, what is the phase shift due to was the before the unity loop gain frequency, there are two poles and a 0 and the two poles will give you a net phase shift of minus 180 degrees at high frequencies.

The zero will give a phase shift of plus 90 degrees at high frequencies and what we want we want a positive phase margin that is we want to stay from minus 80 degrees. So, this clearly means that the 0 has to occur before the unity gain frequency. If the zero did occur after the unity gain frequency and you had two poles before the unity gain frequency at the unity gain frequency, the phase shift phase would be very close to minus 180 degrees, let me draw it on a different plot.

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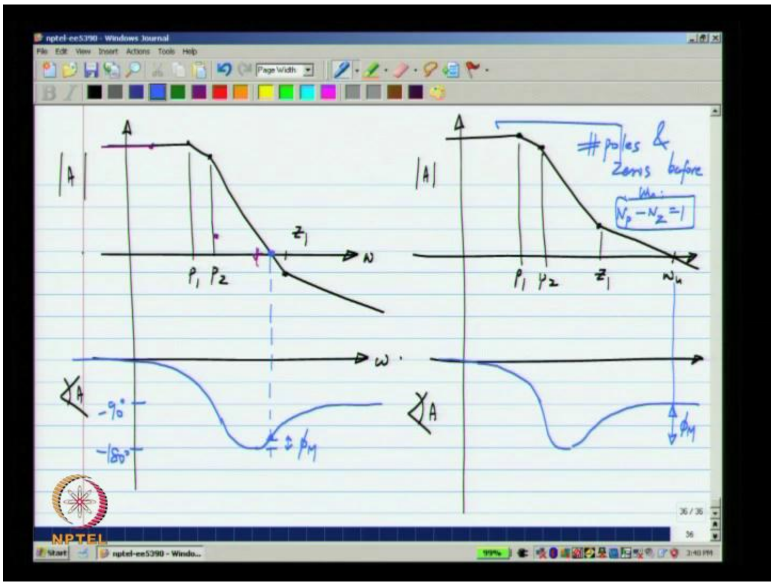

So, let say this is the magnitude plot and I had something like that this is the first pole second pole and the 0 and this is the magnitude plot this is the phase plot and this case phase would start from here and because of these two poles. This is the reason of frequencies which almost minus 180 degrees and because of the 0, come back to minus 90 degree. Now, you can see that the phase margin here is really poor the phase shift at the unity gain frequency this is the unity gain frequency that is very close to minus 180 degree.

So, it is very poor, so this means that the nucleus plot the nucleus plot will enter the unit circle at an angle close to minus 180 degrees. So, this kind of plot is not admissible what we would like to have is a plot that looks more like this poles can be anywhere, but where they can be are a x 0 has to occur well before the unity gain frequency. This is the unity gain frequency for different plot will make it clearer this is the gain magnitude this is the angle. In this case, angle will be it again goes almost to minus 180 degree in this reason, but it comes back to something close to minus 90 degrees by the time the gains drops out to 0 degree, so in this case the phase margin is quite large.

You can very easily see that if you have multiple poles before the unity gain frequency what happens is the phase goes to minus 180 degree or beyond that and only way for the nucleolus plot enter the unit circle in the third quadrant is to have also 0s. Before the unity gain frequency, in fact if you have a three poles before the unity and frequency they will contribute and net phase shift of minus 270 degrees, but I want a net phase shift of between minus 90 minus 180 degrees at the unity gain frequency.

So, that is means that I have also have two 0s, so in fact the number of poles and 0s before the unity gain frequency should be such that the number of poles minus number of 0 is 1. Earlier, we are stability criterion and differently, in fact we are only looking at cases where there was a single pool before unity gain frequency or unity loop gain frequency to be precise. We could have more poles beyond the unity loop and frequency and we said that they should be recently far sufficiently beyond the unity loop and frequency. Now, that was a restrictive case it is not necessary that the we have a single pole before the unity loop and frequency we can have multiple poles, but we should also have 0s.

So, the phase come backs to somewhere between minus 90 degrees minus 180 degrees; that means, this phase ship can go to high values, but then the nucleus spot has to enter the circle in third quadrant that is for the phase shift of minus 90 to minus 180 degree. So, this in terms means that if you have n p poles before the unity gain frequency should have n p minus 1 0s also. So, the phase shift comes back to somewhere between 90 and 180 degrees phase lack this will be becomes even more clear when we discuss the three stage of the free forward of Op amp. It is possible to have Op amps with the multiple poles before the unity loop gain frequency, but they also have to have 0s.

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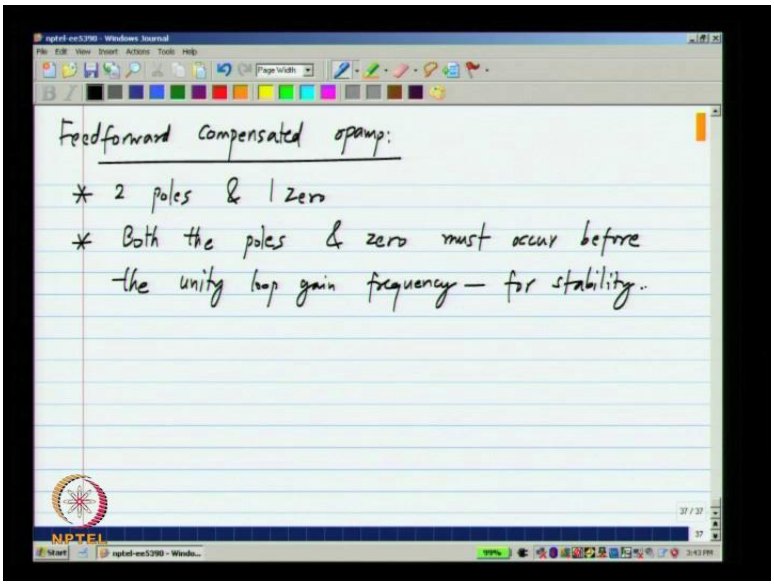

Both the poles and 0 must occurs before the unity loop gain frequency or stability, now we are not said the what is the factor by which 0 has to be before the unity loop gain frequency. We will work it out, but it has very clear that for that the 0 has come before the unity loop and frequency. Now, before we analysis, the feed forward f Op amp that we have more we can try and make it m better, just like we a want from two stages miller compensated Op amp of three stages. We now have a better Op amps compare to the single stage Op amps, there is the feed for the compensated Op amps and we can use the idea in a regressive passion.

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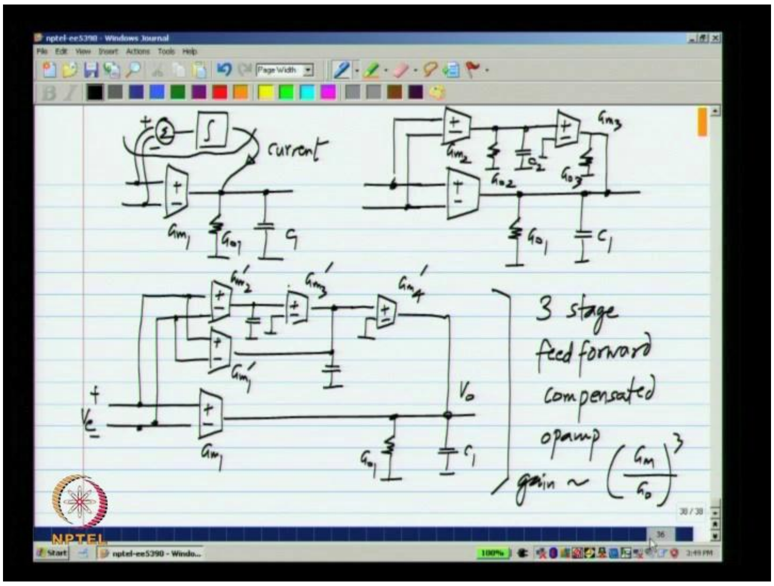

This is the original idea to the difference between these two and integrated and push a current here. So, the current that has to f go in G 1 comes from this path not from G m 1 it comes from G m 1, there has to be different between these two, what it comes from integrator, they does not have to a difference between these two. So, this part we implemented using the simple Op amps that is we took the difference, these two integrated at converted the integrated voltage to current and cut it to final output. The integrator themselves are imperfect, but we saw what the effect of the those things works what enough.

Now, this is what is known as the two stage feed forward compensator Op amp, now to realize this integrator, we can use the two stage feed forward compensator Op amp, instead we earlier used the single stage of Op amps. This is integrator differencing and integration of form by this G m 2 and this capacitor see two and that forms a single stage Op amps.

Now, we can use a two stage feed forward compensator Op amps in its place because that is are better integrator, what we get it if we do that, let me draw my G m 1 G o 1 c 1, because it lack of space. I will not show the output resistance of this transconductor, what they are there. Now, this is my two stage feed forward compensator Op amp which behaves like an integrator. Now, I have to convert the integrated voltage to a current a period to the output, I call G m 1 and those things you can now see that at DC all the capacitor are opens. So, basically when will have three stages in cascade here two stage in this cascade through this path and single stage by input to the output, this is the input of the Op amps that is output.

So, DC gain will be of mainly due to this stage and cascade stage it is really product of these three DC gains plus a product of these two DC gains plus this particular DC gain, but you expect that the product o f three DC gain will dominate. That will contribute chief to the DC gain. So, just like from when we went from two stage miller compensator Op amps two three stage compensator Op amps. They got a higher DC gain here also and we go from two stages feed forward compensator Op amps to the three stage free forward compensator Op amps. You will get a better DC gain, but it needs this other structure you can.

In fact, thing the some counter part of the three stage of the value compensated Op amps. So, when we want high DC gains you can go for three stages and also feed forward compensated and the DC gain will be approximately the cube of DC gain from each stage. Here, I am not writing the specific equation G m by G o, I consider to be a kind of gain that you can get from the single stage. So, G m by G o cube is the kind of gain that you get from a cascade of three stages and what you get form the three stages free forward compensated Op amp.

Let it be for today, in the next lecture we will look at the Bode nucleus plot of the three stage feed forward compensator Op amp. This is mainly to understand stability, when you have multiple poles and 0s before the unity loop and frequency also for the two stage feed forward compensator Op amps. We will reversely evaluate the poles and 0s and see how close the 0 can be to the unity loops frequency because we only said that the 0 has to be below the unity loop and frequency, we will not said how much that will do in the next lecture.

Thank you.