Analog Integrated Circuit Design
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Lecture - 18
Feed forward Compensated Opamp-Typical Opamp Data Sheet

Hello and welcome to lecture 18 of Analog Integrated Circuits Design. What we will do is, first of all, today is to look again at the stability with a two stage feed power opamp and as times how far the 0 must be from the unity loop gain frequency. So, for all we have set is that it has to be within the unity loop gain frequency. We have not discussed how much. Thus, what we will do?

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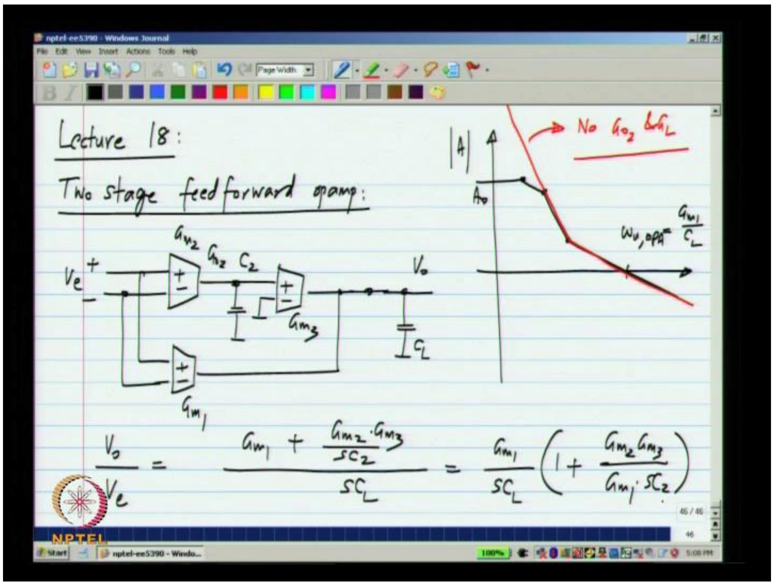

Now, I will assume that here is a plot conductance g l and c l. This is the model wave we have been using. G l observes the output conductance of these trans conductors as well and there is a 0 2 here and c 2. This is the input to the opamp and this is the output of the opamp. We know that bode plot of a or v naught by v e is of this type, right, two poles and a zero before the unity gain frequency, and the unity gain frequency itself equals g m1 by c l because in this region of frequencies, only this path is active and we have g m1 divided by s c l to be the approximate transfer function.

Now, what we want to do is to evaluate the expression for the close loop gain, and this is placed in feed back. Again, we will just do the simpler case of a unity feedback. If you have any other feedback, you have to substitute the unity gain frequency of the opamp by the unity loop gain frequency appropriately. Nothing you can do that by yourself. Also, we have a finite dc gain here.

In fact, it is to increase the dc gain that went to two stage opamp, but if you put all of this detail into the expressions while evaluating stability, it becomes quite complicated. Also, I have mentioned earlier that the stability depends on what happens in this region, what happens to the loop gain in that region. We know that the stability criterion which is the nocuous criteria or talks about encirclement of minus 1 0 which relates to how the loop gain behaves around the unit circle, where it enters the unit circle from. So, we have to model this part accurately, but this part around d c is not so necessary.

So, what we will do is, we will act as though the dc gains infinite which is clearly unrealistic. As I said, it is because of finite dc gain that we go to a two stage or structure and three stage structures and so on, but here we are only looking at stability. So, I will remove this conductance's which makes the gain infinite. The gain is finite through this also, infinite through this path. The bode plot will look something like that. This part will be the same and will have that one. Both the poles will be at the origin and we do not have conductances. That is what is going to happen, but this is accurate in this region.

So, it is perfectly fine. So, with this simplification transfer function of the opamp v naught by v can be written as we know that v naught has a contribution from g m 1 and g m 3. The current in g m 1 and current in g m 3 get added up and pass through c l. So, the total current divided by s c l is the voltage. So, we will have s c l in the denominator and will have g m 1 plus the term representing the current coming out of g m 3, which is g m 2 by s c 2, that is the transfer function from e to this note, and from there to here is g m 3 and this can be written in many forms. I will choose a particular form for convenience. I will write it as g m 1 by a c l, two times 1 plus g m 2, g m 3 by this c l times, sorry g m 2 g m 3 by g m 1 times s c 2. Now, this is in a slightly non-standard form, but it is convenient from our analysis.

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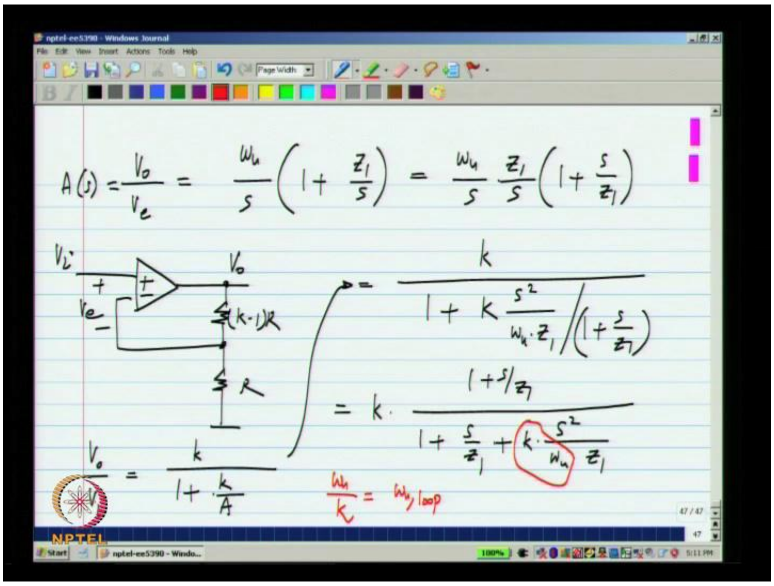

So, v naught by v e is of the form the unity gain frequency of the opamp. I will just refer to it as omega u divided by s, that is what is outside that is g m 1 by c l, g m 1 by s c l plus c 1 by s. Normally, we express things as polynomials in s, but in this case I have the opposite. This can also be written again as omega u by s, z 1 by s, 1 plus s by z 1, and this is nothing, but A of s. I know that omega u is g m 1 by c l and this is g m 2, g m 3 by g m 1 times c 2. Let us say I make a unity gain amplifier with this.

No, I will not evaluate v naught by v. Again, we have done it many times. It will simply be k by 1 plus k by A. I said a unity gain amplifier, here I am making a amplifier of m k, not to unity gain and this will be nothing, but k times the reciprocal of this whole thing. This is A. So, 1 over A is s square by omega u times that one-th divided by 1 plus s by z 1 which when expanded becomes k 1 plus s by g 1 plus s by g 1 plus k s square by omega u g 1. Now, the d c gain is k exactly because we assume that the output conductances are not there. So, the d c gain of the opamp is infinite. There is a 0 in the close loop transfer function and there are two poles.

Now, how did we evaluate such a case? Earlier, we looked at the damping factor or we can equivalently look at the quality factor, and we saw that there the damping factor was appropriate, that is whether there would be lot of ringing, whether the system was under damped, over damped or critically damped. We will do the same thing over here. Now, we also see that this omega u by k can be sort into the unit loop gain frequency. This is what we have being doing earlier also, right. So, the unity loop gain frequency of the close loop function will be the unity energy frequency divided by k if it is a first order dependence.

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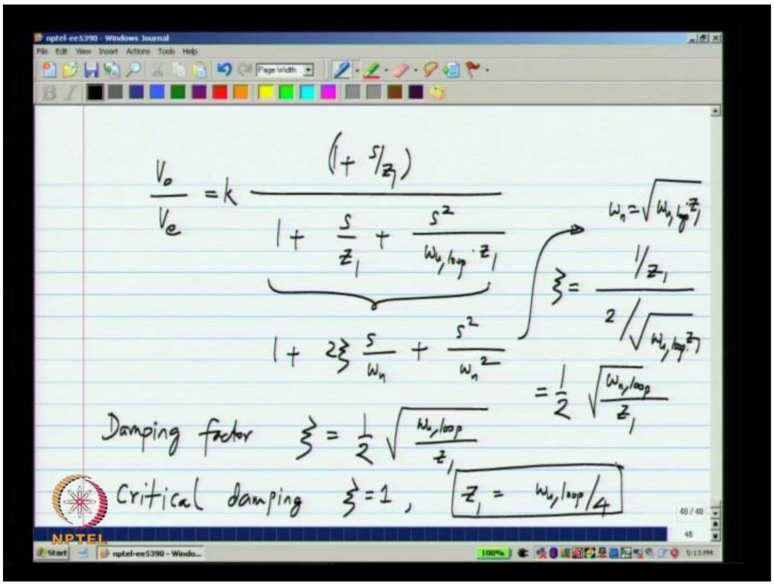

If the loop has first order dependence, that is the case that is what we have and comparing the denominator to the standard form which is what we will get is omega n is square n root of omega u loops times g 1 and zeta will be in other words, it is half square root of omega u loop divided by g 1. So, the damping factor zeta equals half of omega u loop by g 1.

If you want critical damping, we can evaluate it for whatever we want, but for critical damping zeta equals 1 which means that g 1 should be omega u loop divided by 4. This confirms our earlier intuition that 0 must lie within the unity loop gain frequency because we have two poles within the unity loop gain frequency for stability, for good behavior. We should have 0 also within the unity loop gain frequency. This tells you that for a two stage feed forward compensated opamp, the zero should be four times below the unity loop gain frequency.

In fact, if you recall the case where the opamp was an integrator with a non-dominant pole for critical damping, the non-dominant pole had to be four times greater than the unity loop gain frequency. Here, the zero has to be four times below the unity loop gain frequency. There is some symmetry in the results which also makes it easy to remember.

Now, you also will see that from this particular expression if you move the 0 to lower and lower frequencies, the damping will become more and more. You will have higher and higher damping factors and if the 0 approaches the unity loop gain frequency, if it is equal to the unity loop gain frequency, the damping factor is half which is acceptable, but it will have a slight ringing anything lower than that, then you will have a lot of ringing.

So, now, what is the value that we must really choose? Now, in case of an opamp which was an integrator with a non-dominant pole, the non-dominant pole had to be higher and higher frequencies, but it is actually difficult to push things to higher and higher frequencies because of constraints on power deception and so on which we will see later. We will find that if you say that the non-dominant pole has to be 100 and higher than the unity loop gain frequency, it is a difficult thing to do. In fact, the only way to do that is probably by reducing the unity loop gain frequency whereas, these constraints looks different. This says that the 0 has to be below the unity loop gain frequency. Now, is there any limit to, any lower limit to 0? Let us look at the expression for the 0.

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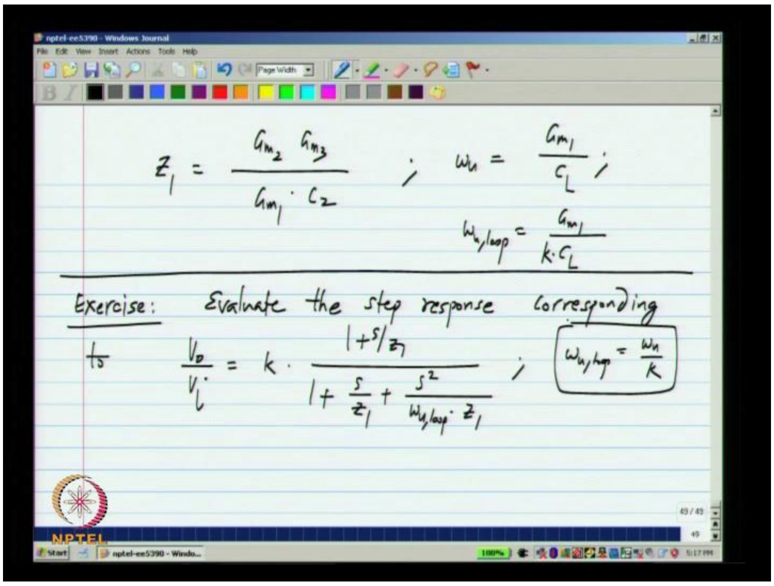

Let me also write the expression for the unity gain frequency which is g m 1 by c l and the unity loop gain frequency of course is g m 1 by c l divided by k. Now, how do we make this 0 smaller and smaller? We could reduce g m 2 or g m 3 or we could increase c 2. Let us say we do not play around with g m 1 because that also influences the unity loop gain frequency, but the other three things we can play around or independently control g 1.

So, it looks like we can make it arbitrarily low, that is we can push the 0 to arbitrarily low frequencies. It turns out that is a great disadvantage. Although the stability criterion is satisfied, there will be other problems. I will not evaluate this completely. Analytically what I suggest that you take it as an exercise and you evaluate the step response corresponding to the transfer function that we have omega u loop of course is omega by k. So, this type some algebra, but with knowledge of laplace transfer, you can do this and also sketch it and see what happens if the 0 moves to lower and lower frequencies, then you will get the point. I will only explain it intuitively here.

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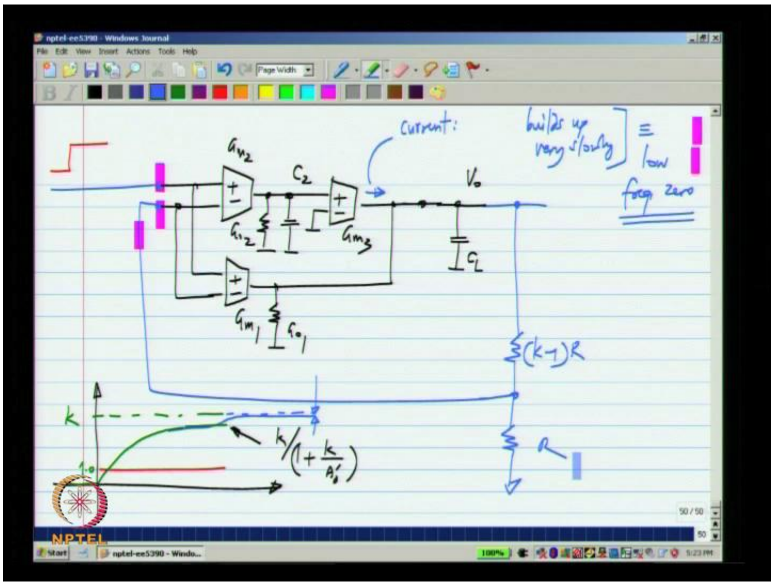

Let me copy over the schematic of the feed forward compensated opamp and what is the amplifier that I built. I took this feed forward compensated opamp and place this in a negative feedback loop. So, what do I mean when I say the 0 is realized at a very low frequency, the 0 is pushed to a very low frequency? Either g m 2 is very small or g m 3 is very small or c 2 is very large. In each of these cases, you will see that either the voltage here is very small or finally, the current output from this is very small, rather it builds up very slowly if you have a given voltage here. If c 2 is very large, it has to charge up slowly and this current builds up very slowly. The current magnitude is very small in the laplace domain, but if you have a step input between these two inputs of the opamp, the current here builds up very slowly that is what it means. So, that is the meaning of having a very low frequency 0.

Now, what is the effect of that? So, that means that let say I apply a step input to this one. Now, initially the output voltage is at some value and it would not change instantaneously because it is a cross capacitor. So, the voltage here, the feedback will not change instantaneously. This is the phenomenon we examined earlier even with an integrator. If you apply a step to the input, the output does not change instantaneously, but it starts ramping up also. Now, we are saying that so effectively, that means between the inputs. So, the opamp you have a step input because this has not changed. We also said that the current that is coming out of g m 3 is very small. It builds up very slowly. So, initially it is very small.

So, initially it is like having only the single stage opamp g m 1 and c l. So, this is all we have. Let us imagine that is g m 2 is very small and g m 3 is very small and c 2 is very large, that is 0 is at a really low frequency, so that this current does not built up much in the beginning time period. So, what happens if I apply unit step? The output is supposed to build up to k times, the unit steps. Let say this is 1 and this is k. Now, since the current is very small, we practically have a single stage opamp in our circuit.

So, it builds up to something and also, we know that the single stage opamp has a very low dc gain. That is because of any resistors loading it, and it is also because of its own internal resistances which I did not put earlier, but this has to be included here. So, it builds up to some value which is basically k by 1 plus k by a naught prime. Here a naught prime refers to the dc gain only of this path g m 1, a g 1 and resistances and so on which is very low. That is why we put the other two stages in the first place.

Now, after a long time the current output of the trans conductance g m 3 starts to build up significantly. So, what happens is after that, after long time this builds up and comes closer. So, although the dc gain of the opamp is high, it takes a long time to reach the low steady state error implied by the high dc gain. In fact, the reason we want high dc gain is, so that the steady state error is very small, but if you push the 0 to a very low frequency, what happens is initially it builds up to a large error which is governed by the dc gain of the single stage opamp found by g m 1, and after a long time you achieve a low stage steady error which is given by the high dc gain of this path.

So, it is not beneficial to push the 0 to very low frequencies. In fact, it is harmful. It defeats the purpose of having a two stage free forward compensated opamp. The reason to go to two stages is first to provide high dc gain, but you have to wait forever to reach that. So, while the 0 has to be lower than the unity loop gain frequency. You can go crazy and push it very low.

Now, you please analyze this using laplace transfer and the conclusion that you draw must be consistent with what I have shown here. You have to plot it for many different cases of 0 to be able to see this. Now, because of this reason, right because the output builds up and then, builds up slowly, this kind of feed forward compensated opamp is not necessarily suitable when you have step like input appears rapidly this single stage response and these two stages response much later. So, for step input, this may not be the best choice, but for other kinds of input where you do not expect a step, the feed forward compensated opamp can give you a very good performance.

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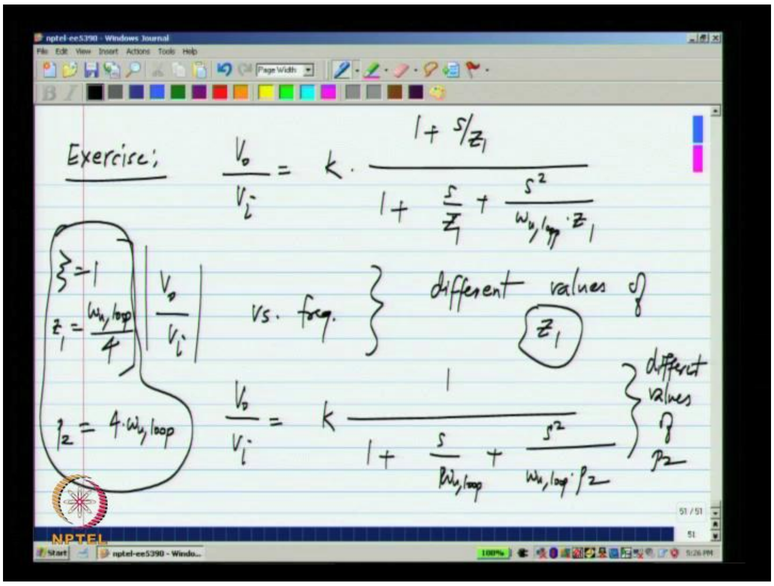

Now, there is another exercise which will just evaluate the effect of the 0. We have a close loop gain v naught by v i to be k times 1 plus s by g 1 plus s by g 1 s square by omega u loop times g 1. So, this is what we have. Please plot the magnitude of v naught by v i versus frequency gain for different values of g 1. You take let us say g 1 to be omega u loop by 4 that corresponds to critical damping. You do that and in particular, contrast this with what we had earlier when we have an integrator and a single non-dominant pole. I believe the expression was something like this, where omega u loop is the unity loop gain frequency and p 2 is the non-dominant pole. The important difference between these two is the absence of the 0.

So, you do this for different values of g 1 here, and different values of p 2 here and you compare the two cases when the damping factor is the same for instant for zeta equal 1. We have g 1 to be omega u loop by 4 or in the second case, v 2 to be four times omega u loop. For the same damping factor, you can compare the transfer function magnitude of v naught by v i over a range of frequencies and then, see how they compare to each other. That also gives you another point of choice when you have more than one solutions. You have to compare two different performance matrix and see which one to choose. It will kind of become obvious why one might be more advantageous compared to the other one. So far we have discussed feed forward compensated opamps which is an alternative way of getting high gains to miller compensated opamps.

Now, you can make feed forward compensated opamps stable. We have to make sure that the number of poles minus number of zeros before the unity gain frequency is 1 at the unity gain frequency. You have only g m 1. The main opamp that you started with that is active. All the other step is active before that and goes away. That is the bottom line as far as stability is concerned. Let say you have a feed forward compensated opamp which you have designed for an amplifier of gain 1 and then, you use the same feed forward compensated opamp and an amplifier of gain more than 1. You may find that it is unstable. This will not happen with miller compensated opamps.

So, feed forward compensated opamps have to be designed for each value of gain specifically, and another issue can be that if the zeros in the feed forward compensated opamps are much lower frequency compared to the unity loop gains frequency, you will have very slow settling effectively. What happens is you have only the single stage acting initially and the other stages which have a multiple stages in casket kicking only much later. So, that means, that the low steady state you are hoping to get by getting a high dc gain will appear only after a long time that limits the speed at which you can operate the opamp, and that can be the limitation as well. So, that tells you that the zeros cannot be pushed to very low frequencies compared to the unity loop gain frequency.

So, so far we have macro models of opamps that is design of opamps at the trans conductor level. We have not yet decided how to make the trans conductors using transistors. That will come in later lecture. We know how to make opamps. We know how to enhance their dc gain, we know the main limitations. What we have to look at next is some macro level characteristics, block level characteristics. So, the opamp that you will see a data sheet and we can guess as what these characteristics just by knowing something about circuits as what limitations they bring in, so that when you look at an opamp data sheet, you will understand what those different terms are.

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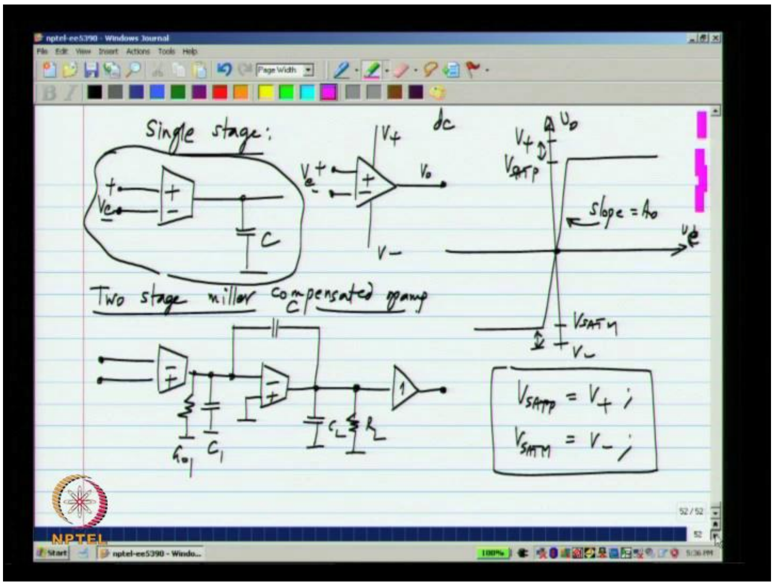

So, I will first start with the single stage opamp. The most opamps that you buy half the shelf and use it in the lab or not single stage by most of them turn out to be two stage miller compensated opamps. This is the two stage miller compensated opamp. The most of the commercial opamps that are available are this variety, but the invariably include a buffer. This is because you could use it with a very heavy loads, so that the behavior of the opamps is not affected sufficiently by the load. So, this is the most popular variety.

Now, what do you see in opamp data sheet? What is it that we want from an opamp? First of all, we want a very high dc gain. So, the dc gain usually given, even the dc transfer characteristics is given d c v naught verses v i. We want a high dc gain. So, that means that we must have a characteristics to the high scope. Now, what happens is that the opamp is operated from some supplies v plus and v minus. There is an upper supply and the lower supply. This could be anything and this is the plot of v naught verses v e v naught verses v e. Now, if you operate from supply range, it turns out that the opamps output voltage cannot go beyond the supply range.

So, let us say the v plus, there is v i minus. There it cannot go above v plus or go below v minus. In fact, it cannot even reach v plus. Usually, it stops somewhere below v plus and somewhere above v minus. This is known as the saturation voltages. I will call it v sat v and v sat m positive and negative saturation voltages. They may or may not be equal to each other. That is the gap between v sat m and v minus. The gap between v set p and v plus may or may not be equal to each other, and you have to determine what v sat v and v sat m are from the data sheet. Now, when that information is not available, it is a reasonable approximation to assume that v sat p equals v plus, that is the upper supply voltage and v set m equals v minus. These things you may know from your basic electronic course, but I am just writing that this is part of the radar sheet. Basically this plot tells you the dc gain, but also the limit of voltages over which you get a high dc gain, we will later see when we make the opamp with transistors exactly what these limits are compared to the supplies that we use.

The important thing also is that it is related to the supplies that we use. Now, this v minus and V plus could be some positive and negative voltages with respect to ground or v minus could be 0, and v plus is the positive voltage and so on. These limits are correspondingly relative to v plus 1 v minus that we use. It is not that v sat p is plus some voltage and v sat m s minus some voltage regardless of the supply. So, that is one limitation. There is limitation on swing limit. Those are the saturation voltages.

Now, in addition to this, it turns out that this can be understood by looking at the single stage opamp itself. It is not only the voltage output of a circuit that is limited. If you realize a trans conductor, the current output from that also will be limited. This just has to with a design of the trans conductors. It will be limited to some high value or low value, but it will always be limited to some value. What does it mean? Again, we can remove this, an output resistance of the trans conductor and analyzer if the current form is limited. What it means is as you go increasing the input voltage to the opamp, the output current will go on increasing, but at some point, it will stop increasing and it will become constant.

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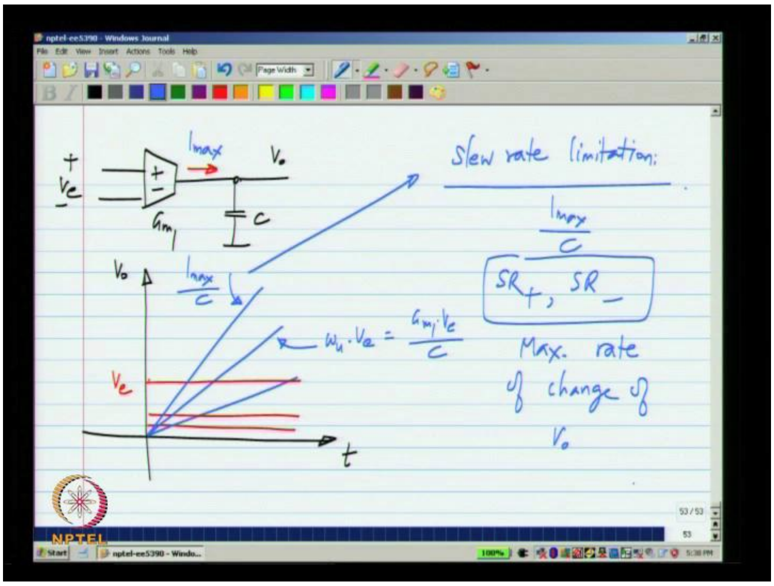

I will simply use g m 1 and c and v e and I look at v o verses t and I assume that v is step of various size, right. So, may be a laplace small step, the output voltage will ramp up. I will apply larger steps to the input. The output voltage will ramp up faster, but what happens is beyond the certain value of the input step, v e the current here does not increase any more. So, let say the current is I max and the slope of the output which should have been, what it should be. It should be omega u times v e.

Now, when the current reaches its maximum value, the output voltage will have a slope of I max divided by c, and it does not depend on v e anymore. Before that it could have been g m 1 times by v e divided by c, but g m 1 times v e, this relationship is avoided only when the output current is below I max. So, it is I max by c. So, what it means is, it is not linear anymore. The output slope does not increase with the input steps and this limitations is known as the slew rate limitation.

The slew rate is given by I max by c and usually, there is a slew rate in the positive direction and a slew rate in the negative direction which can be different from each other, and both these will be specified and this is nothing, but the maximum rate of change of output voltage v o and s r plus is when v o is increasing, and s r minus is when v o is decreasing. Now, when does this come into picture? It comes into picture when you have cases where the output voltage has to change rapidly. This typically happens when you have high frequency voltages of large amplitudes. The output will be limited by slew rate. The output amplitude still may be smaller than the saturation voltages, but the opamp will still behave non-linearly and it scales also when you apply input step to an opamp amplifier.

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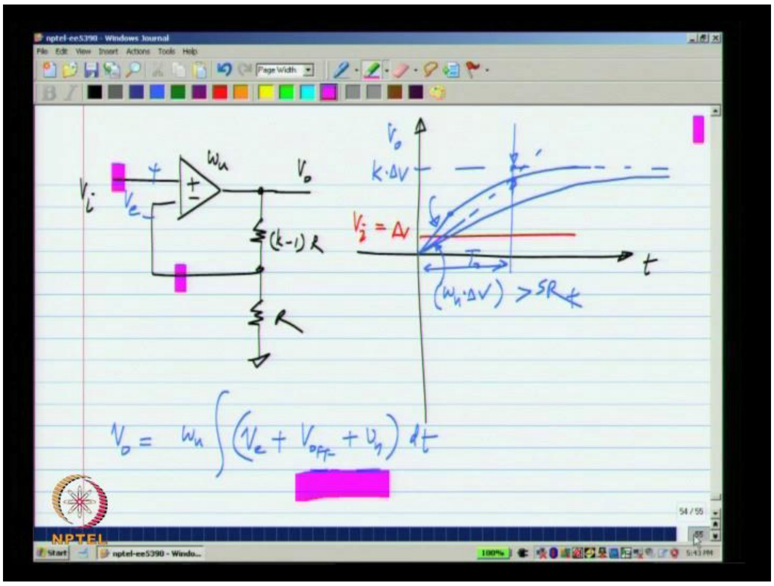

Let say the opamp has the unity gain frequency omega u and I apply v i which is a step of some size, and that is v o. What do I expect if I apply an input step of delta v? This is v i. The output must reach k times delta v. What it does is initially it starts off with a slope of omega u times delta v and then, asymptotically reaches k times delta v. This we have seen earlier in our original analysis of the negative feedback amplifier.

Now, what happens is as you go on increasing the input step, there comes a point where omega u times delta v exceeds the slew rate of the opamps. So, at that point even if you increase the size of the input step, it always starts at a slope equal to the slew rates. At some point, it rescues and it asymptotically reaches k times delta v. So, this means that basically the output will not be linear with the input anymore. So, there is something to be kept in mind. So, these things become important when you are looking at the amount of settling error after a given time. So, let us say after given period t, t naught you are looking at how far the output is away from the desired value of k delta v.

Now, if you assume a linear model, if the opamp is an integrator, this value is some constant fraction of the input. It is related to omega u and the amount of time that you have now because of slew rate, this fraction will not be constant. It will be non-linearly related to the input by this also can lead to non realities and some circuits. So, that is way when using an opamp or when designing an opamp, you have to be aware of the slew rate.

I mean addition to this you know how the opamp works. It compares the input and the feedback quantity takes the difference and integrates the difference. Now, any error in taking the difference means that there will be an error finally because the input to the integrator must be 0 and we assume that the input to the integrator is exactly this minus that one if it is not that right, if the integrated quantity is not v i minus v naught by k.

In general, the input to the opamp is v e and the output should be omega u integral of v e d t. Now, in general, it turns out this is not the case you will have v e plus some other errors. One of them is known as v offset. It is constant with time and there is also a v n which is a noise which is varying with time. Now, these are random quantities. If you measure v off and v n for a large number of opamps, you will find different values for each of them. V off is constant with time, but it is different for each opamp.

V n is randomly varying the time as well as it is different for each opamp. So, these things will cause an error. So, that means that the accuracy to which the feedback quantity, it tracks the input quantity is limited by these numbers. So, we off and v n are also given in the data sheet and the output will have some contribution from v off and some contribution from v n.

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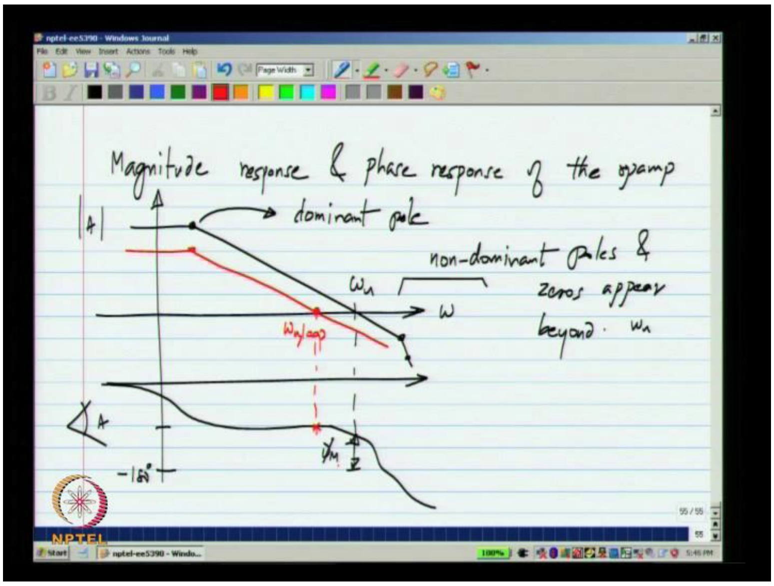

Finally, we also have the magnitude response and possibly, the phase response as well the opamp and these are evaluated with small signals, and this is basically the bode plot of the opamp, so that you can ascertain stability. So, you will be given magnitude of A and angle of A, and most of the commercial opamps will have this miller compensated structure. The dominant pole compensated structure meaning there will be a single low frequency dominant pole below the unity gain frequency of the opamp, and all the non-dominant poles and zeros appear beyond omega u, something like this.

The angle of A also will be given and from this you can figure out the phase margin. This will be the phase margin if the opamp is placed in unity gain; otherwise you have to go to the appropriate gain curve. Omega u by k will be the unity loop gain frequency and you have to look at the phase at that point and ascertain the phase margin of such an amplifier. So, that will be in the opamp data sheet.

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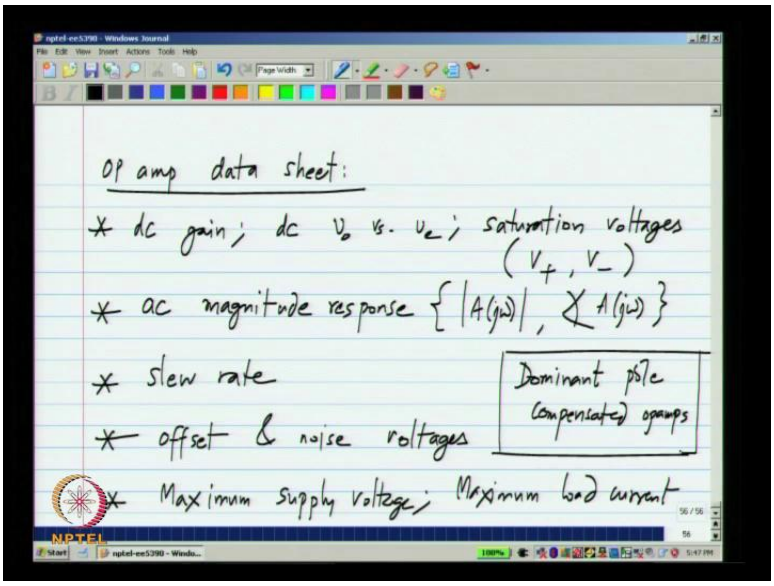

So, when you look at an opamp data sheet, you can expect the dc gain v c v naught verses v e in our notation. V e is the input to the opamp, v naught is the output and this will also include saturation voltages and these are functions of the supply voltages that you use will have the ac magnitude response, which basically means the magnitude of the opamp gain and the phase of the opamp gain, it will mention the slew rate and it will also give you the offset and noise voltages. Exactly how the offset and noise voltages are specified, we will see later. Now, in addition to these things, there may be a number of other limits mentioned, that is maximum supply voltage and maximum load current that it can supply and so on.

So, next time you take an opamp data sheet, please look for all of these things and try to understand where they come from. Now, I said that we will have this limitation. By looking at what happens in a single stage opamp, exactly the same thing happens in multi-stage opamps as well. So, these specifications are general. Exactly how they are related to the topology, we will see when we come to transistor level opamp design and also, the other thing I said was most of the opamps are dominant pole compensated opamps.

So, again these term frequency composition is the term that says that the opamp is made to behave like an integrator around the unity loop gain frequency. That is what ensures stability. Here, things like frequency compensations are used to ensure stability.

What it means is that the opamps characteristics are such that around the unity gain frequency, you have 20 db per decade slope or first order behavior or behavior like an integrator that process of getting that is frequency compensation. In our case, we started with the integrator as the model for the opamp. So, we did not use these terms as often as you may find in other books.

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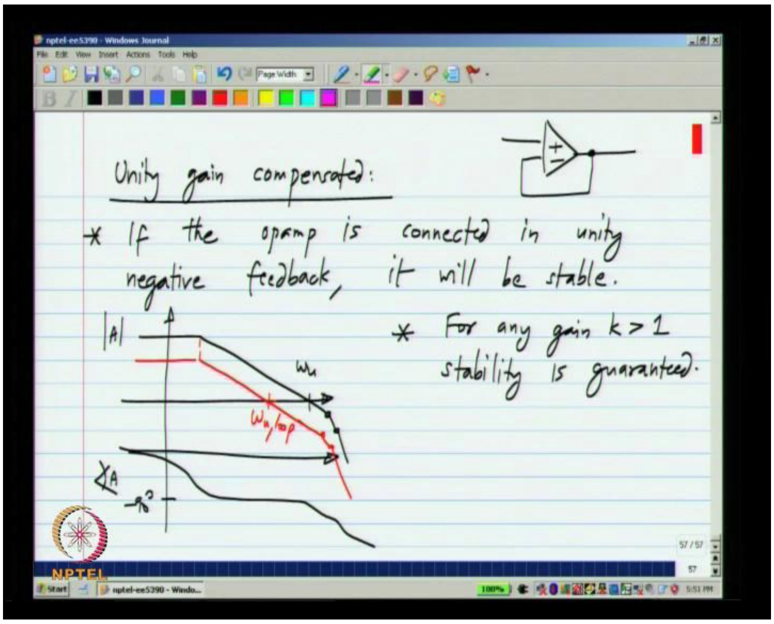

Now, finally one more thing about standard opamps that you see, most of them are unity gain compensated which means that if the opamp is connected to unity negative feedback, it will be stable, that is if you make an amplifier like this, it will be stable. I also said that they are dominant pole compensated opamps. So, the magnitude and phase A do something of the sort and the none dominant poles and zeros occur beyond omega u and you have the angle going of like that because it is dominant pole compensated. If you make an amplifier with any other gain k, the stability is guaranteed. This we saw earlier for larger A value of k, this will be omega u loop.

Now, the stability is guaranteed, but there is a disadvantage. There is a price that we pay by compensating it for unity gain, that is that omega u loop is smaller than omega u. If k is 10, omega u loop is 10 times smaller than omega u. Now, what is omega u loop? It is basically the range of frequencies over which you have significant loop gain. Early on this course, we saw that the negative feedback amplifier behaves more or less ideally up to the frequency of omega u loop because the loop gain is significant up to that frequency. When you make an amplifier with this, the close loop bandwidth will be omega u loop. Now, you intend to make amplifier only of gain 10 or more and you use an unity gain compensated opamp which are the certain omega u. That means, you can get a bandwidth of only omega u by 10 or lower than that, and that is a great disadvantage. Now, this unity gain compensation is not necessary because you never intend to use the same opamp and unity gain mode anyhow.

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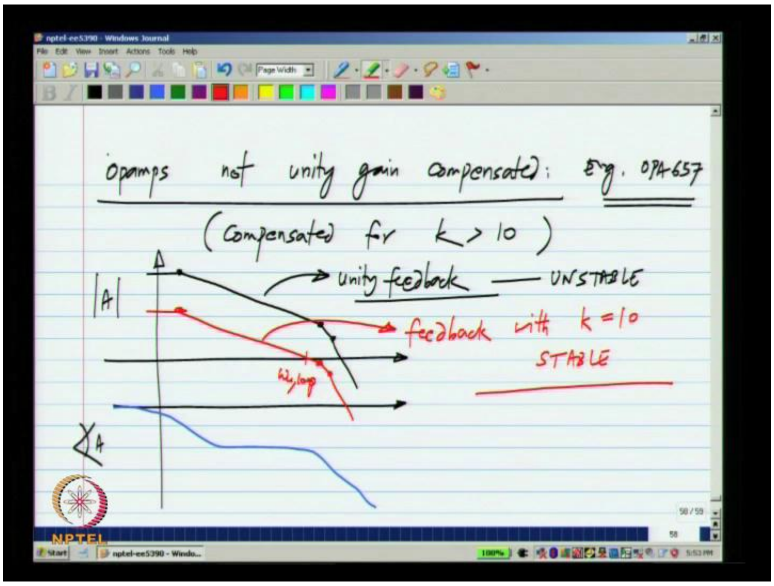

So, there are also opamps which are not unity gain compensated which are available. So, usually these are compensated for k greater than some value. An example of this I think you can see from the data sheet is OPA657. Now, what does it mean to have an opamp that is not compensated for unity gain? Let us say it is compensated only for k greater than 10. So, that means, the bode magnitude plot and the phase plot look something like this. This will have the dominant pole here and if you measure only the opamp, the non-dominant poles occur before the gain of the opamp reaches unity, but you will never put this in unity feedback.

Let us say you put it in feedback loop of gain some 10 also, then what happens is you have something like that where unity loop gain. Now, pulse below the non-dominant poles, the phase of course will be the same for both. This will be the loop gain for unity feedback and it will be unstable, whereas this will be the gain for let us say k greater than 10, and it will be stable for k equals 10 and for any value of k greater than 10, it will also be stable.

Now, this kind of compensation is used, that is the opamp is not being compensated. Unity gain advantages when you want to realize high gains and also, realize high bandwidth because the unity loop gain frequency limits the bandwidth of your circuit. There is no point artificially limiting the unity loop gain frequency by compensating it more than necessary.

So, if you look at the plus seat of this particular opamp, I think it says that it is compensated for gains greater than 25 and it also shows you the response of the opamp when you make an amplifier of gain equals to 25 and so on. Now, by comparing the bode plot of this with some other opamp, that is unity gain compensated, you will be able to understand all these things.

So, thank you. I will see you in the next lecture.