Analog Electronic Circuits.
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Lecture-51.
Op-Amp Compensation, Slew Rate and some Problems.

This is the 51st and the last lecture of this class and we are going to continue our discussion on Op-Amp compensation, slew rate and work out some problems, relevant problems. When I say last, there can be spontaneous expressions. Thank God it is over. Well, it can be on both sides, for the students as well as the teacher. The 1st is the question of compensation. This requires to understand this phenomenon completely, it requires a knowledge of quantities, 2 parameters used to describe system, used to describe the potential instability of a system which is beyond the scope of this course.

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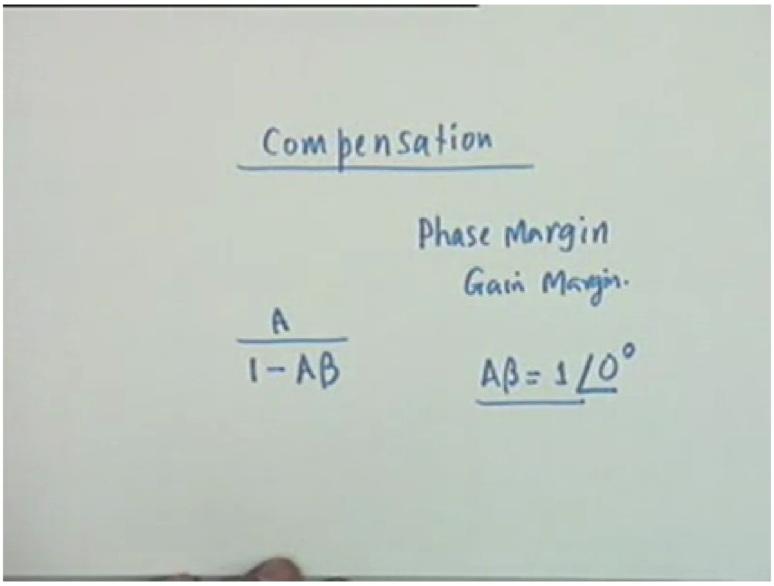

This will be taught to you in the control theory course, 2 parameters called phase margin and gain margin, okay. And these 2 parameters basically can be explained qualitatively as, if you have a feedback amplifier, you know the gain is A by 1 minus A beta, okay and if this feedback is negative, then A beta would have a negative sign, if feedback is positive, then A beta would have positive sign. And the system, the feedback amplifier becomes unstable if A beta is equal to 1 or exceeds 1, okay. A beta equal to1 is the condition for stability, then it becomes an oscillator and it becomes a sinusoidal oscillator, provided there is a frequency selective circuit in the amplifier, okay.

If it is LC, then you call it LC oscillator, if it is RC then you call it RC oscillator. Now in order to keep the system stable we should ensure that A beta never reaches the value 1, okay. This 1 is not simply 1, it is 1, 0 degree. Therefore is in a system, in a feedback system A beta can never reach the magnitude unity, we should make sure that the phase does not reach 0 degree or 360 degree. Is that clear? You see both conditions have to be satisfied, one is that the magnitude should be 1 and the angle should be 0 or an integral multiple of 2 pi.

When in a beta, if in a feedback system A beta can ever reach 1, we make sure that the phase is far away from 0 degree, all right. Now in a system when A beta is equal to1 or the gain magnitude passes the 0 line in dB, okay, 20 log 10 of magnitude A beta, it crosses the 0 dB line, we must make sure that at that point the phase is far away from 0 degree. Suppose the phase is let say -30 degrees, then you have what is called a phase margin of 30 degrees. Is the point clear? There is a margin of 30 degrees, it is like a margin of full-scale paper, you do not write on this, you keep the margin, if this will be this can come here, if necessary you can make it unstable by allowing the phase to go there.

But it is a measure of how safe, how stable the amplifier is. If the phase is let say -90 degrees, well we are safer, we see that the phase margin is larger. In a similar manner…

Excuse me Sir.

Yes?

Is 0 degree precisely defined? I mean if I have a phase of 1 degree…

Yes, if it is 1 degree then it is stable. It has to be, well, it depends on the magnitude, magnitude can be greater than 1, that is good, because that is more positive feedbacks anymore oscillations, more unstability. But the phase, phase has to be exactly 0 degree, okay, there can be a safe margin because of instability, there are noise margins, noise always makes contributes to frequencies which can have a phase close to 0 but not exactly 0, okay. It is a hazy picture at that point but if you want to make a stable amplifier, the Op-Amp you know is always used with feedback and therefore one has to make sure that it always remained stable.

Now the other quantity is the gain margin, it says that if the phase ever reach 0 degree, then you must make sure that the gain magnitude A beta magnitude is far away from one, okay. The magnitude is to be less than 1, okay, it cannot be greater than 1 because greater than 1 still satisfies the conditions of instability, okay. So suppose again at the point at which the phase is 0 degree is half, we say the phase, the gain margin is half. Is the point clear? If it is 0.1, then we say that the gain margin is 0.9. These are qualitatively the concepts, quantitative definitions and they use this in the design of control systems will be talked about in the course of controls.

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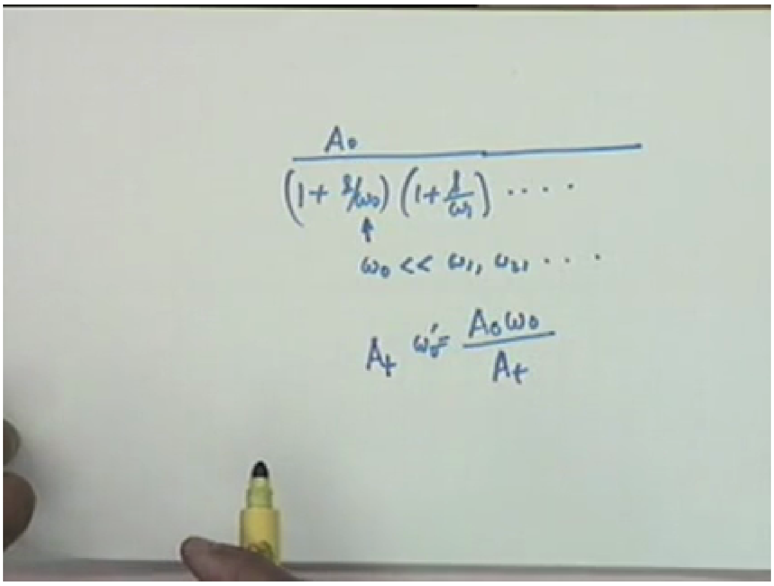

In an Op-Amp, in an Op-Amp as you know there are many transistors and therefore many poles and high-frequency 3 dB point will be a contributed effect of all these poles. To make it absolutely stable, what we do is we create a dominant pole and the dominant pole is to be at a sufficiently low frequency so that if I plot A J Omega magnitude versus amega, we create a 3 dB point in the open loop case at a sufficiently low frequency Omega L of the order of 10 hertz. So that at higher frequencies where the high-frequency poles occur, the gain a sufficiently low so that A beta can never reach the value unity, it is unintentionally, otherwise you have problems, we have problems of instability.

What you consider an inverting amplifier can become unstable because of the phase condition, okay. And this is done intentionally by a very simple technique, one of the simplest techniques is as you know we have the 1st stage as a differential amplifier which is basically a transconductance amplifier and this stage takes it to a gain stage which is basically a CC CE combination, CC CE combination. And what is done is to create a dominant pole, what is done is a capacitor C is connected between the input and the output.

It can be done either internally, internally it can be a fixed capacitor or it can be a custom made. Suppose a particular company says I want 1 million Op-Amps with a dominant pole at let us say 10.35 hertz, then the company to which it orders will make an Op-Amp choose a value of C. Or it can also be augmented from outside, an Op-Amp if you take a chip, there are 2 terminals, these are called compensating terminals and you can connect a capacitor of your choice to make the dominant pole at any frequency that you want. As I said Omega L is much less, I should not call it Omega L, I should call it Omega H, right.

Omega H is much less than than or omega HIs due to the internal capacitances of the transistors so that this pole is the dominant pole and the Op-Amp gain A of S can be written approximately as the A0, that is you can look gain, DC value divided by 1+ S divided by C omega 0, let us call this omega 0.

Sir what do you mean by dominant pole (())(10:20).

Dominant means the effect of the other pole is negligible. Effect of the other pole, in general the Op-Amp transfer function will be of the form 1+ S by Omega 0, then 1+ S by omega 1, etc. etc., in general this would be the situation. If Omega 0 is much less than Omega 1, Omega 2 and so on, you know the high-frequency 3 dB point is basically determined by Omega 0. And the ratio required is 1 is to 3, 3.3 approximately. So this is what is called a dominant pole, this dominates the picture. And it makes sure that any other corner frequency, any other pole frequency, the gain is sufficiently low so that A beta can be never-never reach unity.

This makes the Op-Amp absolutely stable, whatever connections you make, it is done intentionally. It is opposite to our concept of widebanding, widebanding in an Op-Amp is not a problem because you always use the Op-Amp with the feedback. All right, and feedback reduces the gain, our open look gain is of the order of 10 to the 6, 10 to the 6 gain free we required in practice, okay. We require games of the order of 100, 200 and so on, so omega 0 multiplied by the gain, no, omega 0, A0 omega 0, if the gain that you want is AT, then the effective omega 0 prime will be this divided by AT. The gain bandwidth product remains a constant.

And therefore the bandwidth can be expanded to any value that you want, subject of course the highest pole frequency, the highest pole frequency. That is a cannot go beyond let say 1+ S by Omega n. If Omega n is the highest pole frequency, you cannot go beyond because then the things will take care of themselves. And the gain would be reduced to a very small value at that point. So you understand what is a dominant pole. The dominant pole, and this process is called compensation. This is compensation for instability, compensation for instability.

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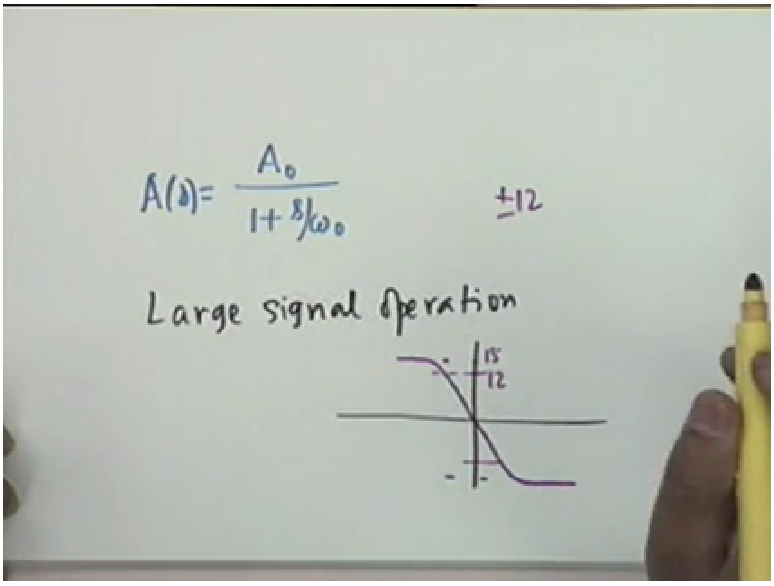

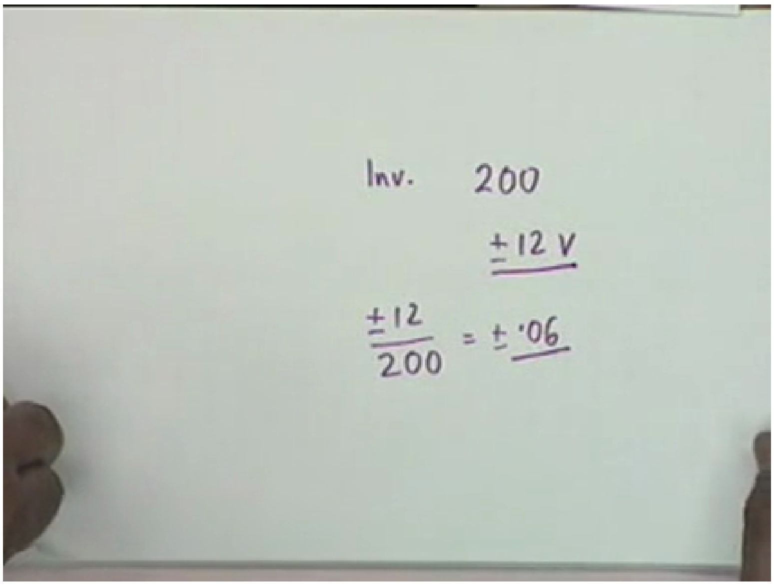

So a usual Op-Amp 741 or any other that you see can always be described by A of S is equal to A0 by 1+ S by Omega 0. And the compensating terminals in Op-Amp chip, if you connect another capacitor that, the small capacitor, this omega 0 can be adjusted to any value that you like, okay. Now this leads us to the large signal operations of an amplifier, the dominant pole has a very statutory effect on the last signal operation of an Op-Amp. As I had commented earlier, if you apply a large signal to the input terminals of an Op-Amp, there is a limit up to which the output can go.

As you know in a, exactly like the differential amplifier, well the output voltage will saturate had some value, ideally the value is VCC minus VCE sat ideally. But since curvature starts even before that, a few volts are left out. If this limit is let say 15, then a typical limit up to which one can go is 12, okay, plus minus12. For example this plus minus12 we have given a name, it was called the output voltage range, output voltage range.

For example if you make an inverting amplifier with let say gain 200, inverting amplifier with a gain of 200. And the output voltage range is plus minus12, all right, output voltage range is plus minus12 then what is the highest amplitude of a sinusoid which you can apply at the input to get the maximum possible output. Very simple, plus minus12 divided by 200, which is plus -0.06 or peak to peak should be 0.12. This you can estimate, the output voltage range will be specified by the manufacturer, this will be specified.

And when you apply an input signal for a particular game, if you take care that you do not apply more than plus -0.06 because then you will get distortions. Now distortion cannot always be judged in a CRO because your eye is a very deceptive equipment. Eye basically is an integrator and what an integrator does is it fails to see the finer variation, it sort of moves out. And therefore one should very religiously stick to the specifications and calculate what is the maximum input that you can apply. Now this, the last signal operation, this is one caution that has to be exercised.

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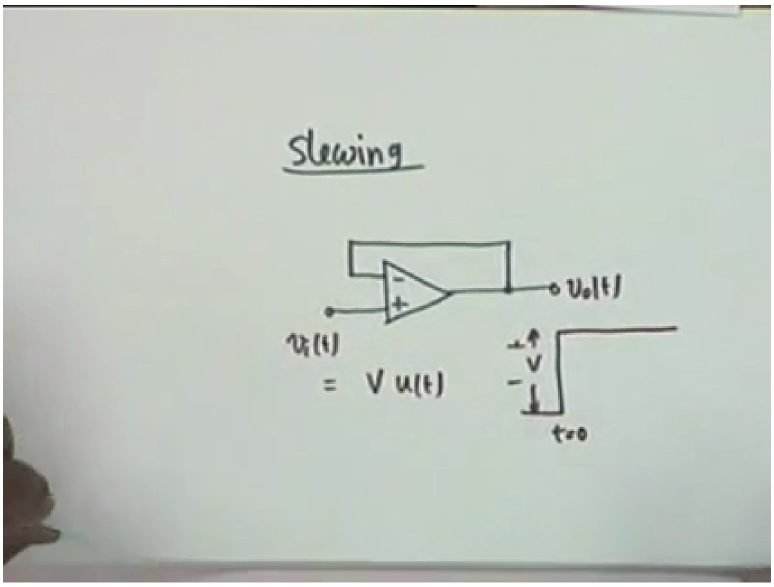

The other is the so-called phenomenon of slewing, SLEWING. To understand slewing let us take a very simple example, let us take a unity gain amplifier. As you know a unity gain amplifier, the input is applied here and there is 100 percent negative feedback, okay. This is a simplest possible Op-Amp application. And of course you know that instead of a short-circuit I could apply, I could use a resistance here without any problem, I could use a resistance here and if I use a resistance here, then I have to use a resistance here also to take care of offset.

Those are final considerations and we must do that as a religious matter, you must not try to fabricate an Op-Amp circuit as is given in the textbook. You do that but you also take care of offset. Now let us apply to this input a V IT, a V IT which is a step, which is a step voltage, let say capital V U of T. The input is a step, , okay, at T equal to 0, occurring at T equal to 0 and the magnitude is V. What do you think, all right, let us find out the output voltage, the V0T under ideal conditions, okay.

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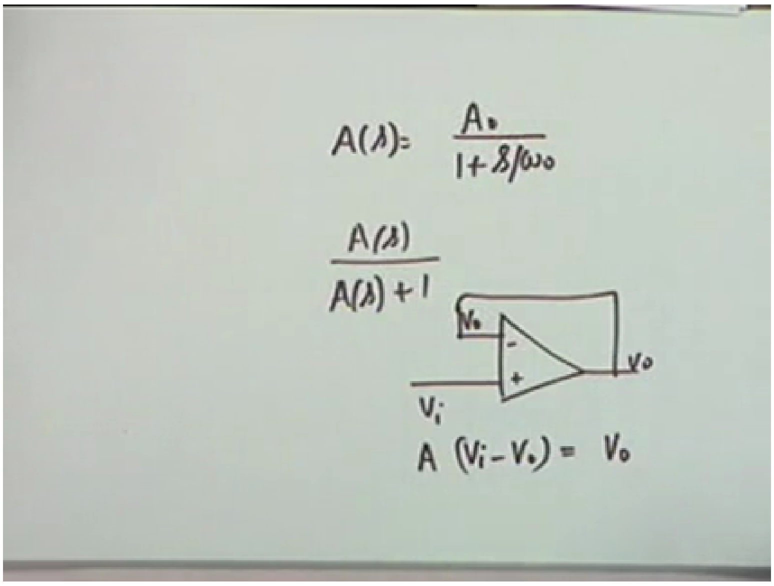

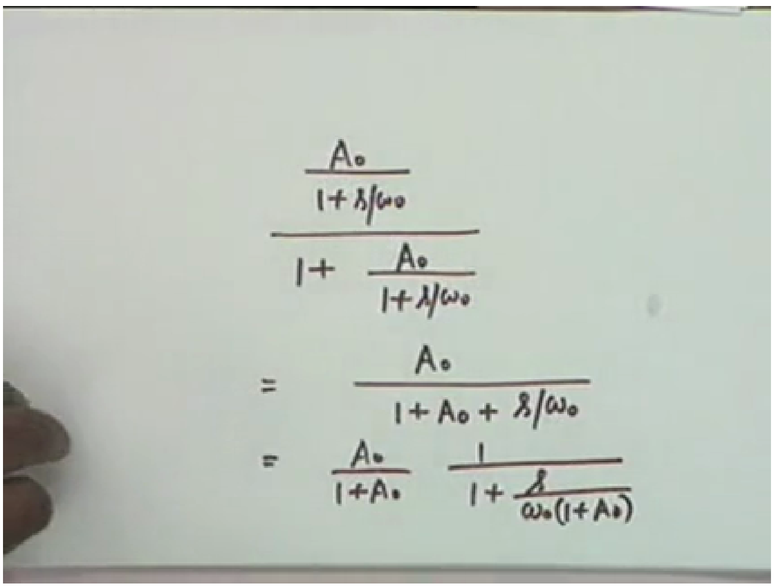

You know the gain of the amplifier is a dominant pole, A0 divided by 1 plus S by Omega 0 and the gain of the Op-Amp under unity gain condition, under unity gain connection is not exactly unity, it is A0 divided by A0 +1, okay. If you analyse this, if you analyse this, the gain at mid-band could be a 0 divided by A0 +1. The actual gain would be A of S divided by A of S +1. Does this surprise you? Yes or no?

How do you get this?

How do you get this, very simple. Okay, let us get this. This is VI and this is V0, this is V0, now I am taking the phasor quantities. So this is minus plus, VI minus V0 multiplied by A is equal to V0. And therefore V0 by VI is A by A Plus1, okay. Now if that is so, obviously the gain of the Op-Amp would be A0 divided by 1 plus S by Omega 0 divided by 1 plus A0 divided by 1+ S by Omega 0 which you can write as A 0 divided by 1 plus A0 plus S divided by Omega 0, all right. That is, since the gain is approximately unity, the bandwidth should be approximately a 0 times omega 0. You can write this as A0 by 1+ A0, 1 divided by 1+ S divided by Omega 0, 1+ A0. Okay.

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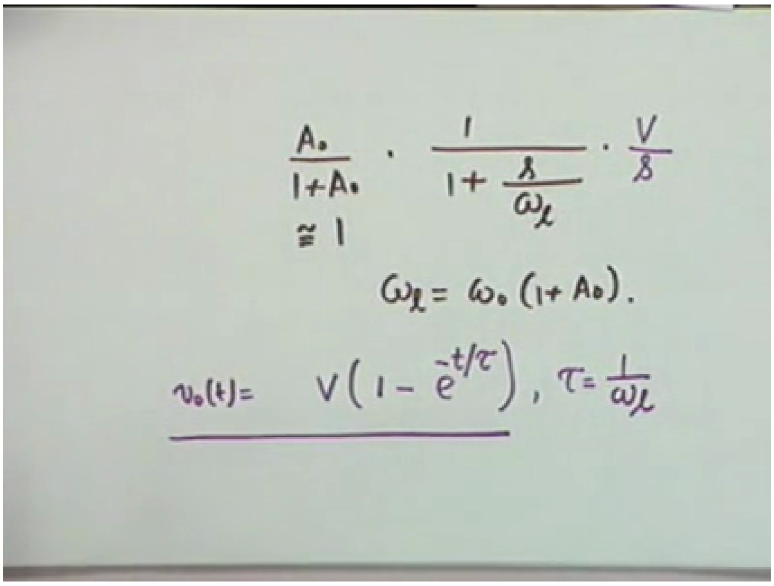

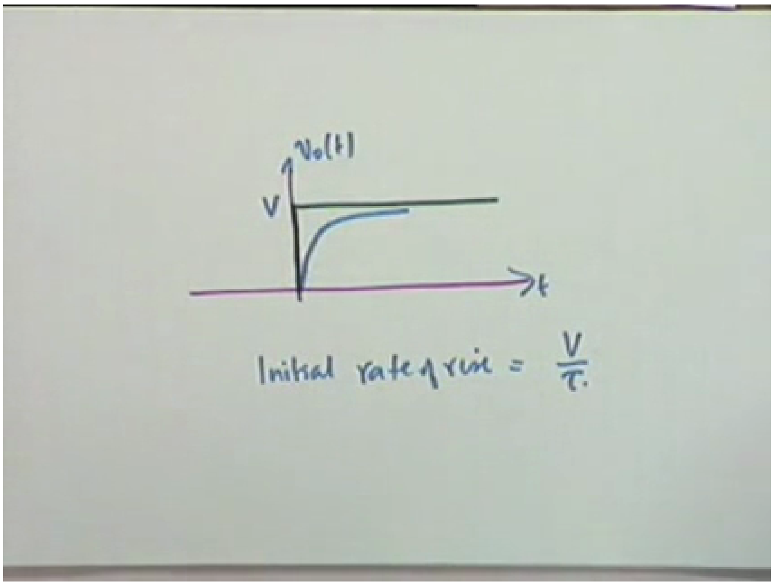

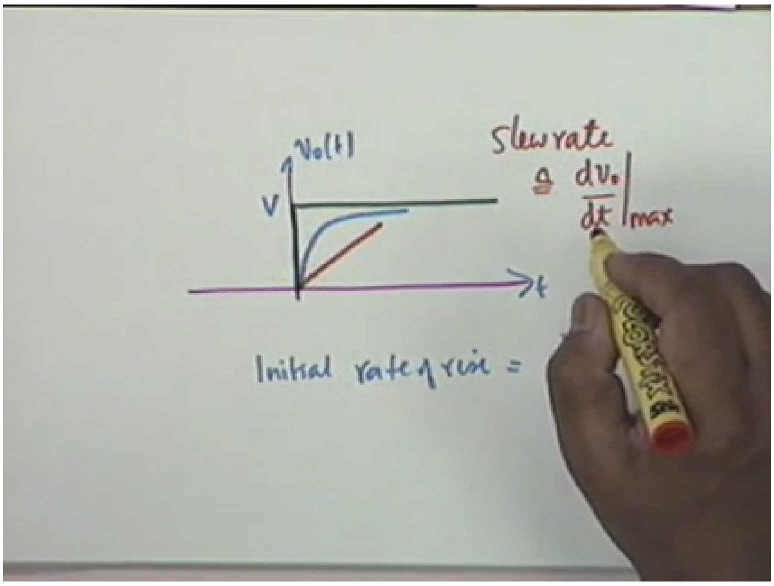

And therefore the bandwidth has been extended to approximately the GBW product. I can write this as A0 divided by 1+ A0 which is approximately equal to 1 multiplied by one by one plus S by let say omega L, the closedloop bandwidth, omega L is equal to Omega 0, 1+ A0. Now if I apply a step of amplitude V, what would be the transform of the output voltage? This would be multiplied by, this is the transfer function and we multiply by V by S, all right.

And if you take the inverse Laplace transform, it is not difficult to see that my output V0T shall be equal to capital V, 1 minus, it is a lowpass circuit, e to the power minus T by Tao, where Tao is equal to, what is Tao, relationship of Tao omega L, 1 by Omega L, that is correct, which predicts that the output voltage shall rise exponentially, okay. If I plot the output voltage, the input is this, the output should rise exponentially like this and go ultimately to V. Unity gain amplifier, so ultimately to go to V, after a long time. What is the initial rate of rise?

This is V0T versus T, initial rate of rise, not 1 by, V by Tao, okay, V by Tao. Alright, it turns out that in that in practice this is not the case, in practice what happens is the output voltage, if capital V is large, if capital V is small, very small step, a microvolt or a millivolt step, yes the rise will be exponential. But if capital T is a few volts let say, large voltage, than it turns out that the output rises linearly, okay. And this, when this happens, we say the Op-Amp is slewing, okay, the Op-Amp… Pardon me?

Please repeat this.

If capital V is sufficiently large, then the output does not, does not rise exponentially, it rises linearly at a much lower rate, okay. And when this happens, we say slewing is taking place, the Op-Amp is showing slewing effect or slew effect. And the slew rate is defined as the maximum rate at which this output rises, okay. That is d V0 dt Max under large signal conditions, under large signal conditions. The reason why slewing occurs is not difficult to understand if you recall that the Op-Amp, how the Op-Amp has been compensated.

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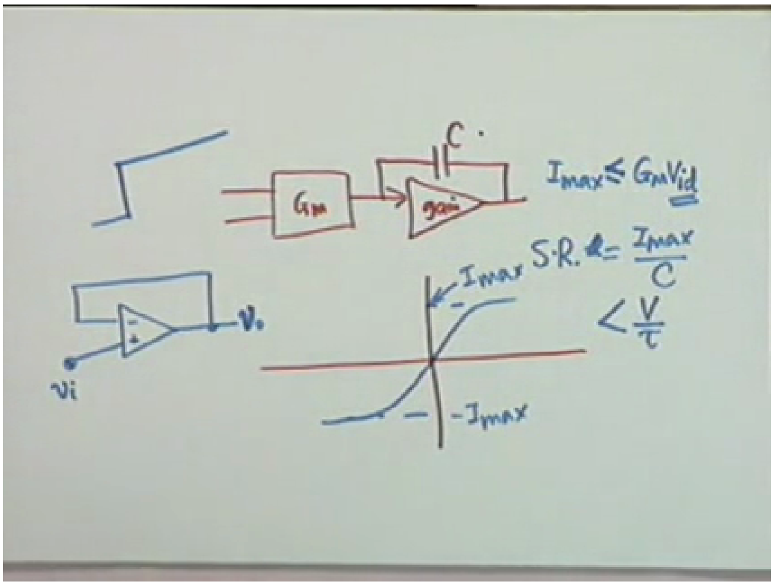

We have 2 stages, one is the transconductance stage and the output is given to a gain stage with a capacitor between input and output, okay. When the input voltage is large, the output current as you know, in a differential amplifier for example, the output current saturates, the output current saturates like this. To what value if it is a differential amplifier with a current source? Biasing IEE, goes to either plus IEE or minus IEE. Let us call this in a general differential amplifier, in general Op-Amp where there may be several stages of differential amplifier, let us call this IMAX and minus IMAX.

Okay, obviously IMAX, what would be the relation between GM V ID and IMAX? If V ID is large, then and the current saturates, obviously IMAX is less than or equal to GM V ID, agreed, okay. So what happens is in the unity gain amplifier, let us draw it again, minus plus, this is the input and the output is taken here, VI, V0. In the unity gain amplifier when the input step is applied, step of amplitude capital V, the output cannot rise instantaneously if it all it has to rise either exponentially or linearly. We will see why linearly but the output at time T equal to 0 is equal to 0, correct. If this is 0 then obviously this is also 0, therefore the whole step is applied between this point and this point.

V ID at T equal to 0 is a large voltage capital V. And what happens to GM, is it saturates? The current output saturates at IMAX and the current cannot vary, this current, this current, you see this step, then remains like this, so this current then charges this capacitor. A constant current charging a capacitor gives rise to a voltage which is linear with respect to time and that is why the slewing effect comes into operation. And this is purely because of the dominant pole. The dominant pole is a necessity, is a necessity for making the Op-Amp stable and one of the evils that accompanies this is that the output cannot rise exponentially, it rises linearly, okay.

So the slew rate SR is obviously equal to IMAX divided by C, is that clear. The rate at which the voltage rises will be simply IMAX by C and it would be less than V by Tao which is the initial rate of rise of the exponential voltage, of the exponential rise. This is basically the reason for slew rate and slew rate is something which one has to be, one has to take care if one applies an Op-Amp for a large signal operation. We will work out a few examples to illustrate this. Is there any question at this point? No. Since we are not working any tutorial sheet on this, let me give you a couple of examples to solve before I take some examples on slew rate.

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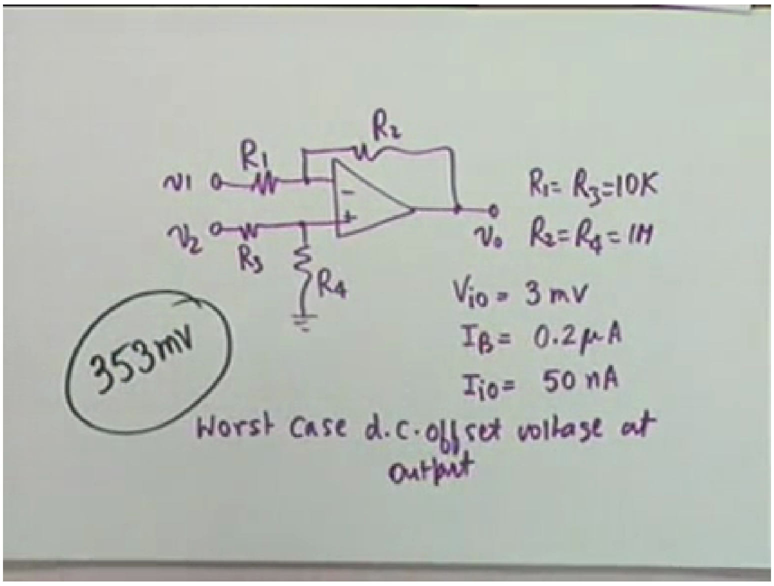

There is an interesting example on the differential amplifier, offset calculation, please take it down, the difference amplifier. This is V0 and you know it difference amplifier is like this, this is V1 and this is V2, I do not know, I have interchanged the terminals, normally small V0 should be proportional to V2 minus V1 and the gain will be determined by these resistances. These resistances are usually proportioned like this, these 2 are equal and these 2 are equal. R1 and R3 are equal and R2 and R4 are equal. Then V0 would be 1 plus R2 by R1 multiplied by V2 minus V1 or V1 minus V2, there will be a sign change.

Now the problem says R1 is equal to R3 is equal to 10k and R2 equal to R4 are equal to 1 meg, so there would be a gain of 100. So V0 would be 100 multiplied by V1 minus V2, that is correct. You must take care of this sign, 100 multiplied by V1 minus V2 or -100 multiplied by V2 minus V1, okay. Now, the question says that all kinds of offsets are present. The offset voltages 3 millivolts, the base, the bias currents are not equal but you know what is the bias current for a Op-Amp, it is the average of the 2, I B1 plus IB2 by 2.

This is given as 0.2 microamperes and the offset current is given as 50 nanoamps. So IB2 minus I B1 or I B1 minus IB2 is 50 nanoamperes, okay. The problem is to find out the worst-case DC offset voltage at output, the worst-case. And my, I have not solved this, my calculation shows that the result is 353 millivolts, this is the answer. If you get the answer, you know how to calculate and you know how to calculate. I said worst-case, that means you need not take care of signs, you take that all of them are conspiring to produce a, to add up, to an output voltage which is the worst-case.

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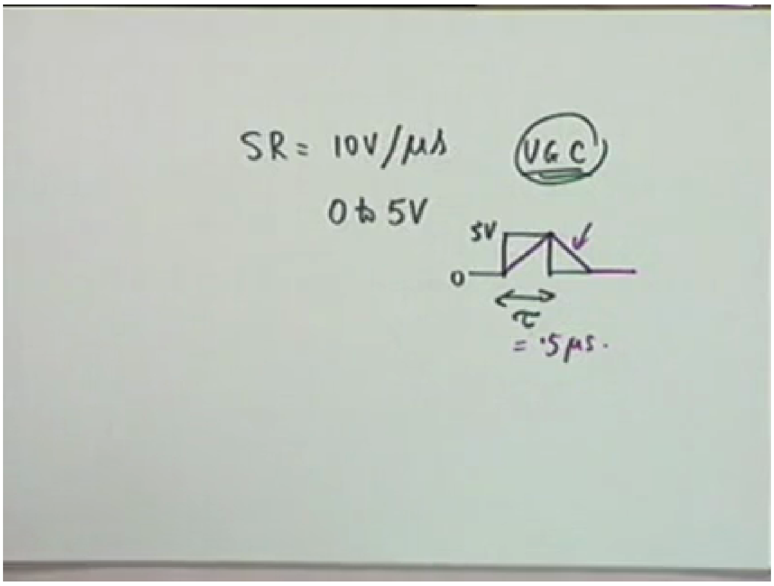

Now a problem on slew rate. For an Op-Amp having a slew rate, typical slew rates are 10 volts per microseconds, slew rate is the rate at which voltage rises, so its dimension is voltage per seconds, okay. And volts per microseconds, this is the Op-Amp slew rate and the Op-Amp is connected in the unity gain connection, unity gain configuration, UGC, okay. The input pulse rises from 0 to 5 volts, it is a pulse, not a step. What is the difference between the pulse and a step? Pulse is the difference between 2 steps, right, it is a staircase, then it must come down, it is a pulse.

The pulse rises from 0 to 5 volts, the amplitude is 5 volts, then it stays for a while and then comes down, come down identically, I mean ideally to 0. The question is what is the shortest pulse, what is the shortest pulse that can be used while ensuring full amplitude output. What is the shortest pulse that can be applied, that can be used while ensuring full amplitude output? What is the full of attitude output? 5 volts because it is a unity gain connection. You must, if it was a noninverting gain stage for example of gain 10, then you would have divided by, he would multiplied by 10, okay.

But then you must make sure that does not exceed the output voltage range. We might, there might be a problem in which the VCC is specified to be 15 volt and you multiply it by 100 and it becomes 500 volts, okay, obviously that cannot be obtained. Here it is a unity gain connection, so the maximum output is 5 volts and what we are required to do is to find this Tao for which the full amplitude output is obtained. Obviously and the 2nd part of the question says for such a pulse, sketch the resulting output, okay. Obviously, obviously what we expect is that during the duration of the pulse, well the voltage will rise and the slew rate rise to this value.

If it reaches early than obviously it will have to stay constant for a while, okay. And the maximum rate of rise is 10 volts per microseconds, so what is Tao? 0.5 microsecond. And what would be the resulting output? Is this the output, will it say like this? No, it must come down symmetrically, it cannot come down exponentially because again the discharging is in a linear manner, okay. So it will come down like this. Once the slewing has started, no exponentiation, it is linear. So this is the output, shape of the output pulse. 2nd problem…

Sir but the reverse current might not be considered then?

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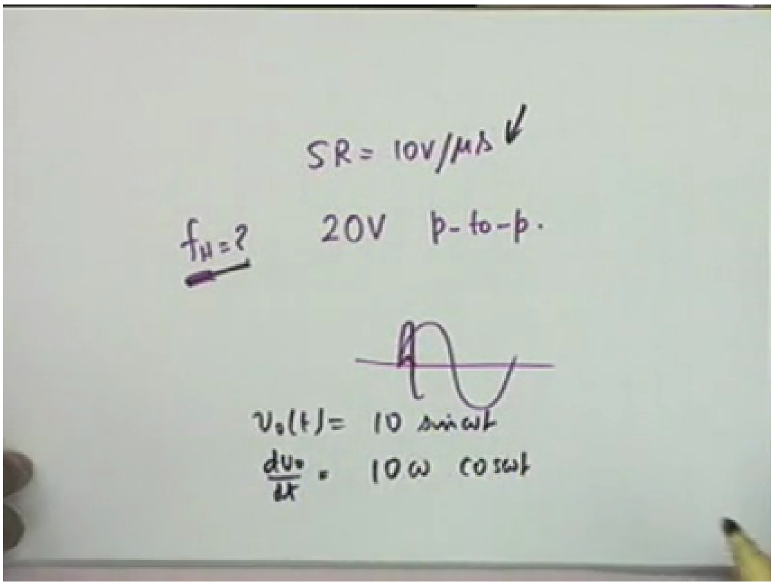

Reverse current might not be, there is no other way, the capacitor has to discharge and the transistor maintain its current constant. Okay. The 2nd problem is the following. For an amplifier with the slew rate, same, 10 volts per microseconds, it is a typical values for 741, what is the, you see this question is slightly twisted. What is the highest frequency at which you are required to find out the highest frequency at which 20 volts peak to peak sine wave can be produced at the output. 20 volts peak to peak sine wave output can be produced at the, at the output, sine wave can be produced at the output, is the point clear.

20 volts peak to peak, that means the maximum amplitude can be 10, okay. Why does it depend on frequency? Because frequency determines the rate of rise. For a sine wave the rate of rise is determined by the frequency, if it is higher frequency, it will come down like this. And this rate of rise cannot be accepted, cannot be handled by an Op-Amp. If the frequency

is sufficiently high, you will see that it rises like this in a linear manner and it produces a triangular wave instead of a sine wave, okay. Of course it is used for sine to triangle converter, that is another use, using the slew rate you can convert a sine wave to a triangular wave, at high frequencies, yes.

Now, so the question is what is the highest frequency at which a 20 volts peak to peak sine wave can be produced subject to this slew rate? Obviously the solution of the problem is very simple. V0T obviously is 10 sin of Omega T, 20 volts peak to peak means 10 volts amplitude, okay. And therefore dV0 by dt is 10 Omega cosine Omega T.

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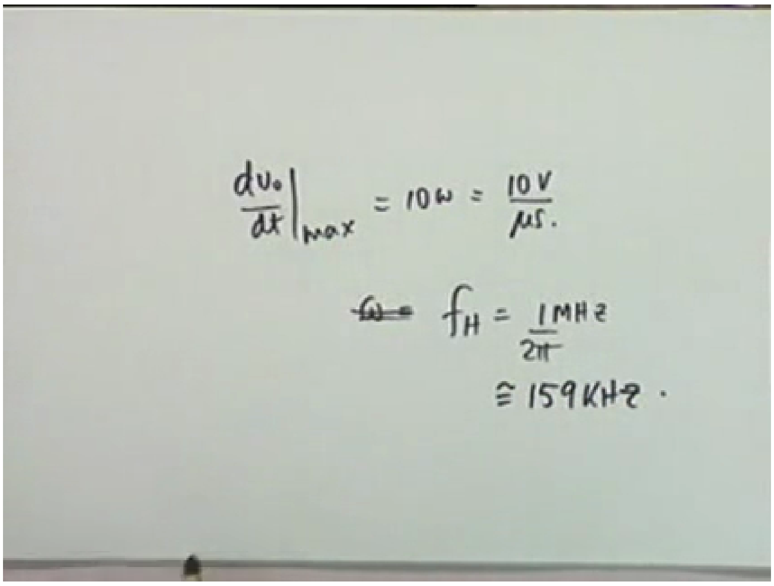

And the maximum value of this, dV0 dt Max is equal to 10 Omega. And that is given as 10 volts per microseconds. And therefore Omega is equal to, FH 1 megahertz, is that correct. 1 by 2 pi megahertz that is correct. All right, that is approximately how much, 159 kilos hertz. Okay, try to work out a few examples from any of the books, any of the books that I mentioned. Every book treats offset, it is a simple problem but one has to understand. This formally brings us to the close of this lecture and this course. I have another few minutes, I want to spend on a message.

Abraham Lincoln, who was Abraham Lincoln? A President of the United States. Abraham Lincoln, when he sent his son to school, he wrote a letter to the headmaster of the school and he, he made some requests to the headmaster to some principles to his son. That letter is a classic letter, if you have not seen it, you cannot see it now because I have made an adaptation from that and that is the message that I want to pass to you. A copy of this will be available, after the class you can pick up. But I want to read this to you and I want you to listen to it.

This is from a teacher to his students, this is an adaptation. You of course know that all men are not just and that all men are not true but also remember that for every scoundrel there is a hero, that for every selfish politician there is a dedicated leader, how true. Remember that for every enemy there is a friend, remember that a rupee earned is of far more value than 5 found. You must learn to loose and also enjoy winning, steer yourself away from envy if you can, it is not, it is not simple, if you can. Learn the secret of quiet laughter. I cannot explain this phrase to you, it has to come from within. Learn the secret of quiet laughter and once you learn it, you will enjoy it, I can assure you.

Appreciate the wonder of books, textbooks for example, but also have quiet time to ponder the eternal mystery of birds in the sky, bees in the sun and flowers on a green hillside, if you have time to observe. Remember that it is far more honourable to fail than to cheat, it is true for all classes. Have faith in your own ideas, even if everyone tells you including your teacher, that they are wrong, have faith in your ideas. Ankur stood tough on the face of a challenge and he won, his answer was correct. You remember that challenge?

Yes Sir.

I appreciate that, I hope Ankur will stay like this throughout his life and you will instil others to stay like this. Be gentle with gentle people, it is important and tough with the tough, okay, do not yield. Try not to follow the crowd when everyone is getting on the bandwagon, because in the class is applying abroad for a scholarship, that is no reason why you should also. Listen to all men but also filter, particularly after learning so much of filtering in this class, you should be able to filter all you hear with the screen of truth and take only the good that comes through.

Try to laugh when you are sad, again I cannot explain this to you, it is only spontaneous, it has to come from within, you have to try, try to laugh when you are sad, be assured that there is no shame in tears. If tears come, let them go, let them flow, do not stop them, there is no shame in tears. Close your ears to a howling mob and stand and fight if you think you are right for a right cause. Expect to be treated gently, IIT boys after graduation have a lot of expectations from the outside world, this is very important in that context.

Expect to be treated gently but do not allow yourself to be cuddled because only the test of fire makes fine steel, only the test of fire makes fine steel. Have the courage to be impatient but also have the patience to be brave. Have sublime faith in your creator, if you are an atheist ignore this, Have sublime faith in your creator and faith in yourself too because then you will always have faith in mankind. This is a big order I know but please see what you can do. Thank you.