Basic Electronics
Learning by doing
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Lecture – 29
Characteristics of Operation Amplifier
(Transfer Charateristics, Gain Bandwidth, Slew Rate….)

Hello everybody! In our series of lectures on basic electronics learning by doing we will move on to the next. You might recall that we have been discussing over the past couple of lectures on the characteristics of operational amplifiers.

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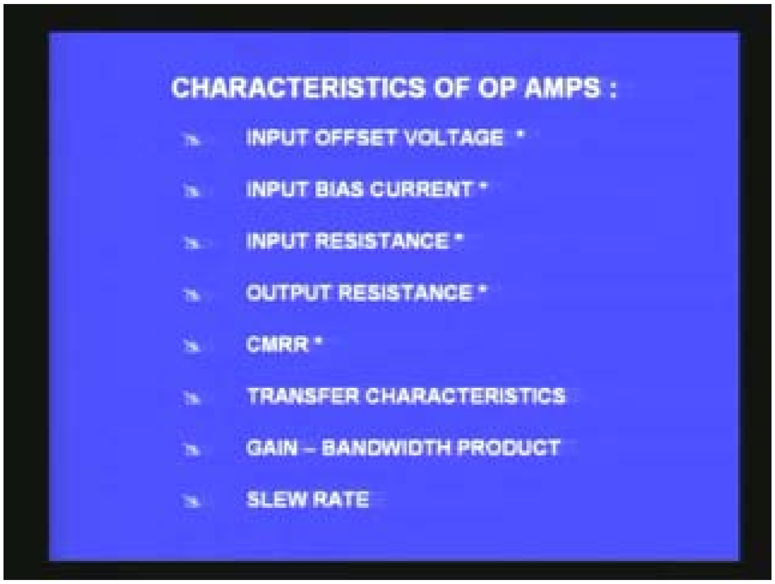

You can see on the screen I have listed the different characteristics that we should normally worry about namely input offset Voltage, input bias current, input resistance, output resistance, CMRR, common mode rejection ratio and then transfer characteristics between the input and the output of the amplifier, gain bandwidth product and finally the slew rate. There are a few more characteristics about which perhaps we won't go into the details. But you might also recall that several of these characteristics we have already discussed in our previous lectures up to for example the common mode rejection ratio and we also performed experiments to really measure these characteristics of the amplifier in the laboratory.

Today we will try to discuss the transfer characteristics, the gain bandwidth product and perhaps the slew rate of the operational amplifier. What is the transfer characteristic? I had just few minutes during my last lecture where I explained about the transfer characteristics. I would quickly recapitulate what we discussed last time and try to go ahead further. The transfer characteristics corresponds to the input and output characteristics of the operational amplifier.

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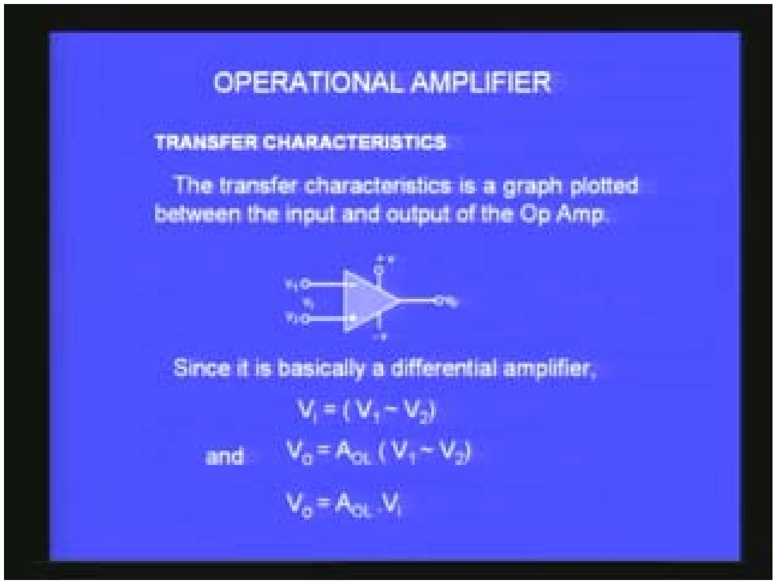

You have an operational amplifier with the two inputs V_1 and V_2 corresponding to the inverting and non-inverting inputs and you have the outputs and the V plus and the V minus corresponds to the power supply. The operational amplifier is basically a differential amplifier. The input voltage which is available between the two input terminals V_i is nothing but the difference in voltage between V_1 and V_2. The output voltage is equal to the gain of the amplifier which I indicate here as A_{OL} multiplied by the exact input voltage V_i or in this case V_1 difference V_2. This A_{OL} is actually called the open loop gain; OL means open loop. This is the gain open loop gain; that means we don't have any feedback provided in the amplifier. Then we call that as an open loop amplifier, open loop gain. Basically it is a linear amplifier. Output should be proportional to the input and the proportionality constant is what we call the amplifier gain. V output is equal to A_{OL} multiplied by V_i.

If I want to understand about the transfer characteristics of the amplifier all that I have to do is vary V_i and look at what happens to V_o and draw a graph between V_i and V_o. That graph will correspond to the transfer characteristics between the input and the output. Typically for an operational amplifier the open loop gain is about 10 power 5. For example in the case of 741 which is the most popular operational amplifier the value is close to 10 power 5 or 100,000. That is the total gain, open loop gain without any feedback. If I give 1 volt differential input between the two inputs then what will be the output? Going by the equation that I already gave you V output is equal to A_{OL} into V_i that means 10 power 5 into 1 will be the output voltage.

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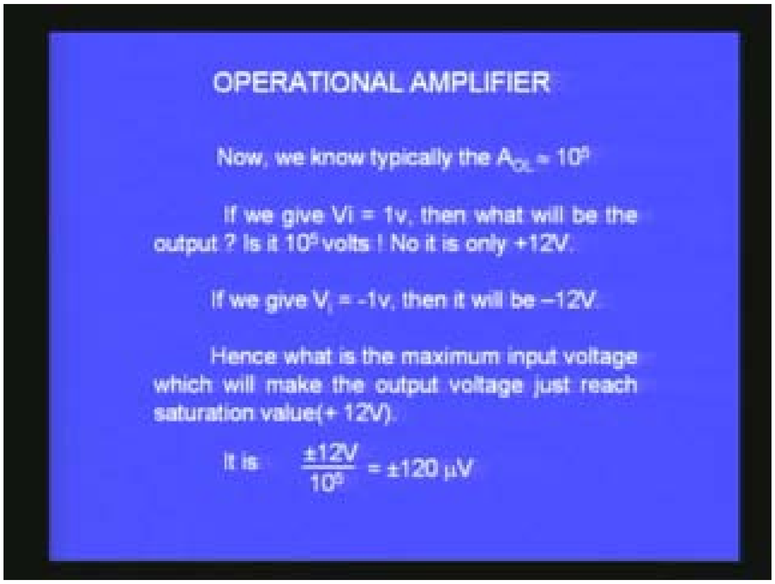

V output will be 10 power 5 volts. That's what you would expect. Can it be 10 power 5? No way. Because in any amplifier the output cannot be larger than the power supply voltage that they have provided. It is the dc power supply, the energy from that power supply we are using to perform this action of amplification. It is against all basic principles of physics that we can get an voltage which is much larger than the maximum voltage that we have in our battery. If I give 1 volt I will not get at the output 10 power 5 volts but I will only get the maximum voltage that is possible to get from the amplifier and the maximum is very close to $+V_{cc}$ and the minimum is close to $-V_{cc}$. The V_{cc} in this case if I assume to be + or -12 volts the output voltage can never be greater than +12 volts or -12 volts irrespective of whatever may be the input I give. The amplifier cannot be an amplifier for all types of input voltages. This is a very important idea.

We can try to look at the range of input voltage for which I will get a well defined amplifier behavior which is characterized by the equation V output is equal to A_{OL} into V_i which I showed you already. Similarly if I give -1 volt as the differential input, the output voltage will again be -12 volts. That will be the maximum or minimum that I can get on the output. The output cannot be different from +12 volts to -12 volts. Anything beyond this limit of +12 volts to -12 volts is not possible at the output. This output restriction will automatically give me a restriction on the input if you want to look at this as a good linear amplifier and let us try to recalculate the maximum input voltages corresponding to +12 volts. Input voltage can be obtained as +12 volts divided by the open loop gain 10 power 5. + or - 12 volts divided by 10 power 5 gives me 120 microvolts. I have multiplied numerator and denominator by 10 to make it 120 by 10 power 6 volts and 1 by 10 power 6 is 10 power -6 that is nothing but microvolt. What I get as the limits of the input voltages between the two input terminals is + or -120 microvolt. So this is the maximum range of input voltage that I can give for which the operational amplifier will perform like a normal amplifier. Output will be related to input by a factor which is called the open loop gain. If I give any voltage beyond this + or -120 microvolt the output will saturate at +12 volts or -12 volts depending upon the polarity of the input.

If I want to transform this into a graphical representation how will it look like? I have the V_i on the x-axis and the V_o on the y-axis. Because I can have both plus and minus my axis also goes on both sides; plus side and the minus side. This corresponds to $+V_i$ and the this side corresponds to $-V_i$. Similarly we have $+V_o$ and $-V_o$. I also mark on that a 12 volts point; +12 volts and -12 volts for reference.

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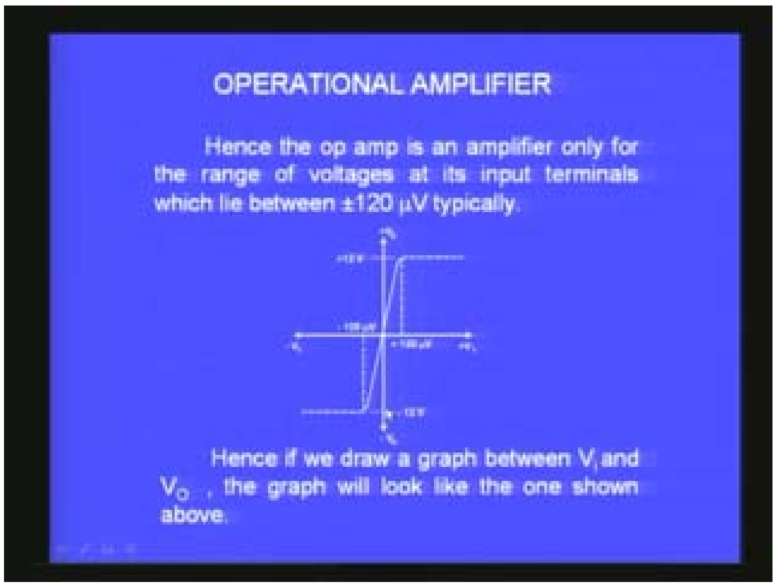

I start from zero for my input voltage. This is V_i. If I keep increasing my input voltage slowly along the V_i axis that means I have a power supply with which I can increase the voltage and I apply between the two input terminals and keep increasing it so that I get 10 microvolt, 20 microvolt, etc and till I come up to 120 microvolt I can have almost linear behavior at the output. The output voltage also increases linearly. But the moment I go beyond +120 microvolt the output will remain at +12 volts for all input voltages which are larger than +120 microvolts. That is why you get a horizontal portion here. This corresponds to a saturation of the output. Similarly when I look at the negative side if I keep increasing my voltages on the negative side -10 microvolt, -20 microvolt, etc till I reach a point corresponding to -120 microvolt I will get the linear behavior. The corresponding output will also be A_{OL} into V_{in}. It will also be negative. Therefore it is shown on the bottom direction which is the negative y-direction and there is a linear relationship between the input and the output till I reach a minimum of -120 microvolt. Beyond -120 microvolt the operational amplifier output saturates at -12 volts. This is what I already explained to you and the operational amplifier transfer characteristics will look exactly like what I have shown on the screen. There is saturation up to -12 volts and then there is a linear portion crossing through the origin and again I have saturation at +12 volts when I come from very deep minus voltages to very large plus voltages. This is the characteristic I will get.

This has got very good applications. Especially non-linear applications of the operational amplifier are very, very useful. You can use the amplifier in other applications where it is not the amplifying action which is going to be useful to us in different circuits. But this characteristic that it is able to distinguish between two voltages which are varying at the two input terminals within + or -120 microvolts then the output shows a sudden variation from anywhere between -12 volts to +12 volts and this variation switching at the output will be very, very useful for applications where the operational amplifier will not be a simple linear device but it will become a non-linear device and basically it is called a comparator. We will discuss in more detail about the behavior of the comparator and we will discuss several other circuit configurations related to comparator.

I would show you an actual demonstration where I will connect an input signal between the two input terminals of the operational amplifier and we will observe the output V_o not by using a multimeter but we will connect an oscilloscope so that we will able to sweep the input and input voltage between the two limits. For example if I apply a sine wave input with an amplitude of 1 volt keeping the other input zero then with reference to the other input this input will go +1 volt and -1 volt and we can see what happens to the output when this input is given. That will give us an idea of the transfer characteristics of the operational amplifier.

The circuit I have is a very simple operational amplifier the same 741 with the two inputs; one of the inputs is grounded, is connected to the ground. To the other input I am connecting a variable sine wave oscillator and the output is connected to the oscilloscope.

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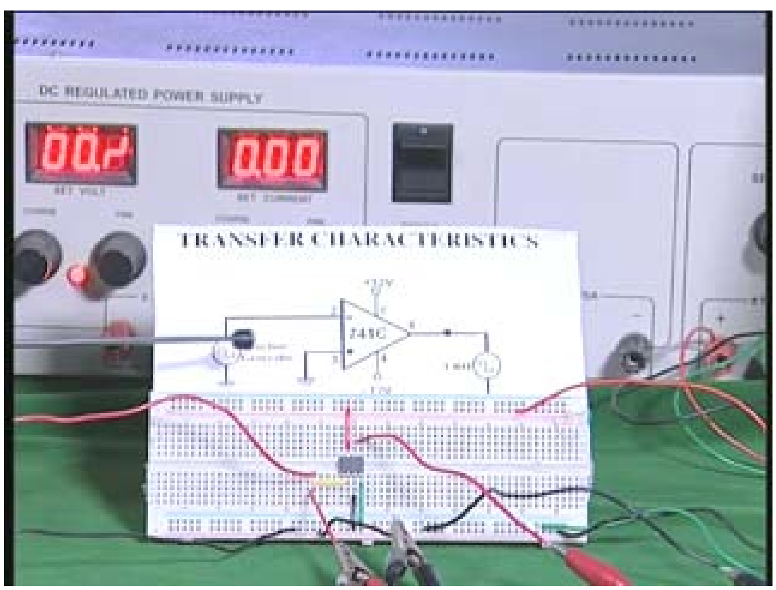

The exact circuit is here. There are no resistors. There are only two inputs and the output is monitored. Both the input and the output are connected to the x and y terminals of the oscilloscope. You have the two inputs x and y. I have used it in the xy mode. In every oscilloscope you have a selection in the sweep generator to put it into off condition.

When you put into off then the two input terminals of the dual trace oscilloscope in general will become the x and y inputs of the oscilloscope and I have given the x from the input corresponding to the x-xis and y corresponding y-xis I have given to the output and this is the signal generator the sine wave oscillator basically from a function generator which can generate all types of wave forms sine, triangular, square, etc and we have put it in the sine and these buttons are for choosing different frequencies. I have chosen around 1 kilo hertz and it is about 1.8. Using this knob I can vary the frequency; using this knob I can vary the amplitude and the output is connected at the input of the operational amplifier. The pin number 2 is connected to the oscillator, pin number 3 is connected to ground as shown in the picture above and the output pin number 6 is taken and connected to the oscilloscope output for the y and one other extra terminal taken from the pin number 2 is given to the x input of the oscilloscope.

I have large amplitude of nearly about 1 volt here using this knob and with reference to the terminal 3 the terminal 2 voltage will go +1 volt to -1 volt and it will keep going up and down. Every time it goes up and down it will certainly cross that 120 microvolt. Beyond that 120 microvolt the output will become saturated at +12 volts or -12 volts as the case may be. What you see behind is actually the dual supply which is connected to the bread board. On the oscilloscope screen you have saturation here and you have saturation here and you have the corresponding slope, large slope.

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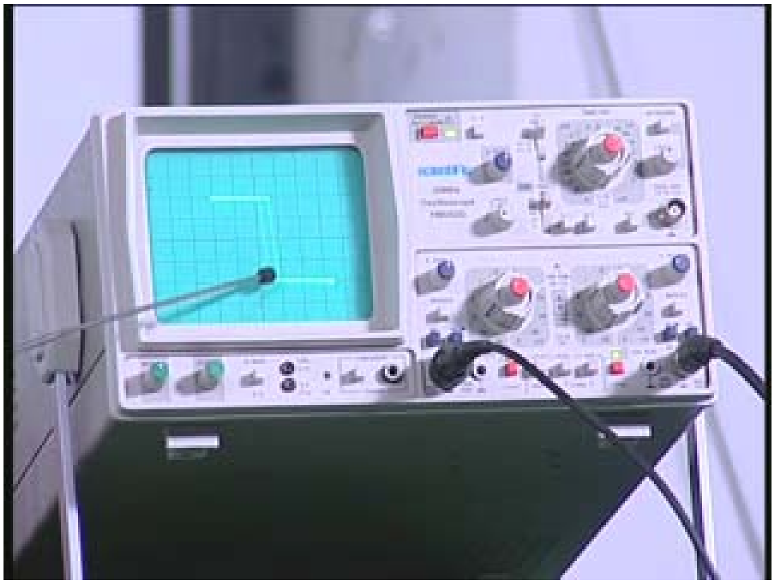

This is linear portion of the amplifier and if you calculate the slope of this vertical line that gives the open loop gain of the amplifier. This gives us a method of measuring a open loop gain also and you can see i don’t know whether you are able to see that a if you come closer and have a look at this you can see there is saturation here there is saturation here. There are two lines here. I did not explain to you about two lines. Why do you get two lines here? It is very simple to understand because when I come from here the moment I cross this 120 microvolts then it will go to the other end and when I come from below it is -120 microvolt at which I will make the transition and these two lines are corresponding to the two limits of that and if I can look at the amplifier position this is at 5 volts. It is about 10 plus something; this also around 10. If not +12 and -12 it is around 10.5 or 11 volts on either side. This is corresponding to -11; this is corresponding to +11 and you have the two lines corresponding to the two limits crossing the x-axis at may be + or -120 microvolts. This is exactly the same as what I explained to you as corresponding to the transfer characteristics and the slope of this line if you expand axis and measure you can measure the slope by knowing what is delta t and the delta v. If you divide the delta t by delta v you will get a number which is actually corresponding to the open loop gain of the amplifier.

Having seen the transfer characteristics of the operational amplifier using an oscilloscope where you can see the two saturation regions corresponding to the output and then you have the two transitions corresponding to the open loop gain when the two voltages are very, very small let us move on to the next characteristic which is called the gain bandwidth product. Every amplifier has got a gain factor. We all know that gain is basically the magnification factor. When I apply an input I get an output which is larger in magnitude corresponding to the input and then only we call that as an amplifier. It amplifies the input signal. This amplifier gain plus another feature of any amplifier is that the amplifier cannot be having the same gain through out for all different frequencies that I give at the input. As I change the frequency at the input the gain can change. In principle an ideal amplifier if I take the amplifier gain should be a constant for all frequencies of the input. But in reality we have already seen when we discussed about transistor amplifiers that because of the several capacitances that are used in the amplifiers there will always be a lower cut off and an upper cut off in frequency beyond which the amplifier will not have a stable gain. This difference in the two frequencies the lower cut off and the upper cut off is what is commonly known as bandwidth of the amplifier.

In the case of an operational amplifier there are no capacitors in general. In the design of these operational amplifiers there is only one capacitor. For example in the case of 741 when it is designed using the silicon chip it is all an integrated circuit. That one capacitor is meant to make the output gain fall at a steady rate and that is the reason why that capacitor is introduced into the design and that is around 30 picofarad, which is the actual value of the capacitor. There are no capacitors as such at the input side and it can amplify even dc signals which correspond to zero frequency. The lower cut off for the 741 or any dc coupled differential amplifier is zero frequency; that means dc. But you will always have an upper cut off corresponding to the capacitor that we have introduced as I mentioned already, the 30 pf. The gain will start rolling down, rolling off at the output at a steady rate and that will decide the bandwidth of the amplifier.

But the point that I am trying to tell you here is that the product of the gain and bandwidth for an amplifier is generally a constant. That means if I have small gain that amplifier can have large bandwidth. If I have large gain that amplifier will have only a small bandwidth. There is a trade off now. If I want good bandwidth then I should try to keep the gain of the amplifier low enough. If I want very good gain then I must make sure that I don't look for a large band width. It cannot happen because the product is a constant. That is what we call a gain-bandwidth product.

On the screen I have shown a board plot. What you see on the screen, the graph is called a board plot. You have on the x-axis logarithm of frequency and you have on the y-axis the gain and this gain also is in logarithmic scale.

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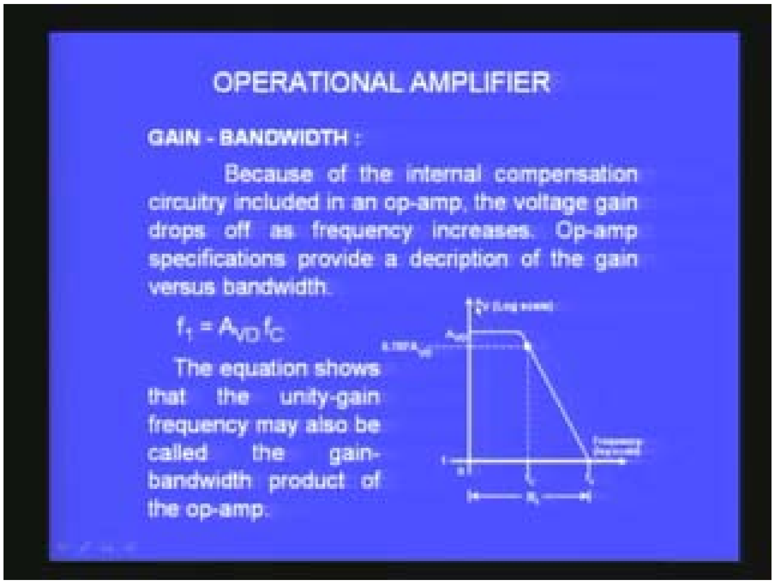

That means there is 1 here starting at the bottom. Then you have 10, 100, 1000, 10,000, etc. It goes in logarithmic scale and similarly in the x-axis I have zero frequency then I have 1 hertz, 10 hertz, 100 hertz, 1 kilo hertz etc. This is also logarithmic scale; this is also logarithmic scale. Then this is called board plot and if you look at the A_{VO}, that is this is the open loop gain this point should approximately correspond to 10 power 5 for the case of 741 because that is the magnitude of the maximum gain that I have at zero frequency and this is 10 power 5. But the 10 power 5 for a short distance is constant. Beyond that it is rolling off; it is coming down on a very steady rate and this is corresponding to the role of the 30 pf capacitors. That I already mentioned to you and so this is the role of and you find if i want to measure bandwidth the bandwidth is generally defined How do you define the cut off frequency for knowing the bandwidth? I should know what is the cut off frequency? The cut off frequency is not the knee portion where it starts bending. It is actually the point where if it is a voltage amplifier the voltage gain becomes 0.707 times the mid frequency gain. This maximum gain multiplied by 0.707 wherever that gain is achieved that point, that frequency on the x-axis will correspond to the upper cut off.

This I explained to you when I discussed about the frequency response of transistors and amplifiers. It comes because of the power coming down by half the value corresponding to the maximum gain. Power half means voltage gain. In terms of voltage gain it will become 1 by root 2 and the value of 1 by root 2 is 0.707; 1 by 1.414. That is the reason why you have here a lower cut off corresponding to 0.707 times the mid frequency gain and that point is the cut off frequency corresponding to the high frequency. This is the cut off point corresponding to open loop gain. This may be about 10 hertz. But if you now reduce the gain instead of 10 power 5 you can get very high bandwidth. The gain-bandwidth product is a constant. What is shown in the graph is corresponding to the gain 1. When the output is equal to input the gain factor is 1. I will get a cut off frequency almost corresponding to 10 power 6. This f_1 corresponding to the D_1 is 10 power 6. Therefore the amplifier has got a bandwidth of 10 power 6. It can amplify up to 1 mega hertz of frequencies at the input if I compromise and decide to have the gain of the amplifier unity.

This will now give us a number corresponding to the product gain-bandwidth because f_1 is nothing but the differential gain multiplied by the cut off frequency. The cut off frequency in this case is 10 power 6 and the differential gain I already mentioned to you is unity. 1 multiplied by 10 power 6 is nothing but the gain-bandwidth product and that is 10 power 6. Once I know the gain-bandwidth product for a given operational amplifier then I can immediately see this second graph shows you all the things. If I want a gain of 10 what will be the bandwidth?

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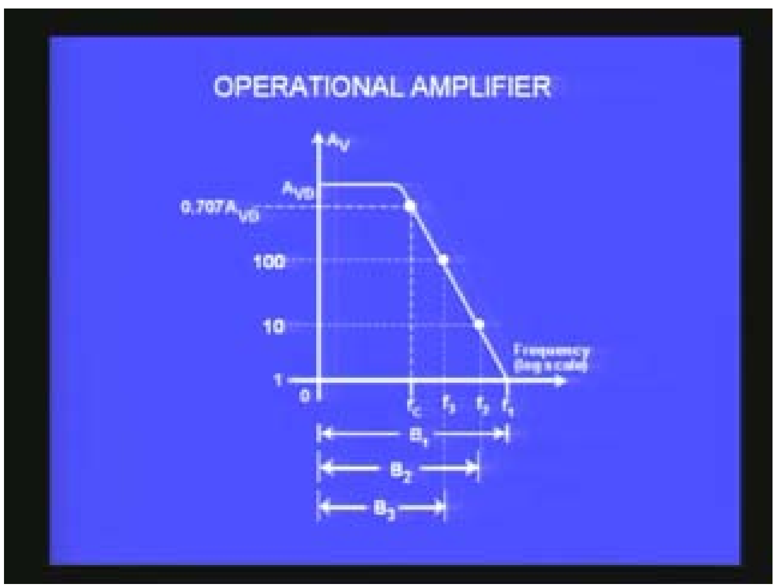

I can quickly calculate because the product of gain and bandwidth is a constant and that in this case is equal to 10 power 6. If I have the gain of 10 the bandwidth should be 10 power 5. That means it can only amplify up to 100 kilo hertz frequencies. If I make my gain 100 then the cut off frequency will be around 10 power 4 that corresponds to 10 kilo hertz and that is what is shown in this graph. For 100 it comes at a earlier point in the frequency; at 10 it comes at a later point and at 1 it almost goes to the point where the graph touches the x-axis. This corresponds to 10 power 6. This will correspond to 10 power 5; this will correspond to 10 power 4, etc. As I keep increasing the gain the bandwidth keep decreasing because the gain-bandwidth product is a constant.

How do we get the gain-band width constant? The simplest method is to make an amplifier with a gain of 1 and apply different frequencies at the input find out where the output voltage decreases from the constant value to 0.7 times the maximum value and at that time whatever is the frequency that gives you the cut off frequency for the output and that in this case when the gain is unity gives you the gain-bandwidth product directly. Now we have taken a numerical example. Calculate the cut off frequency of an op amp having specified values of B_1 equal to 1 mega hertz.

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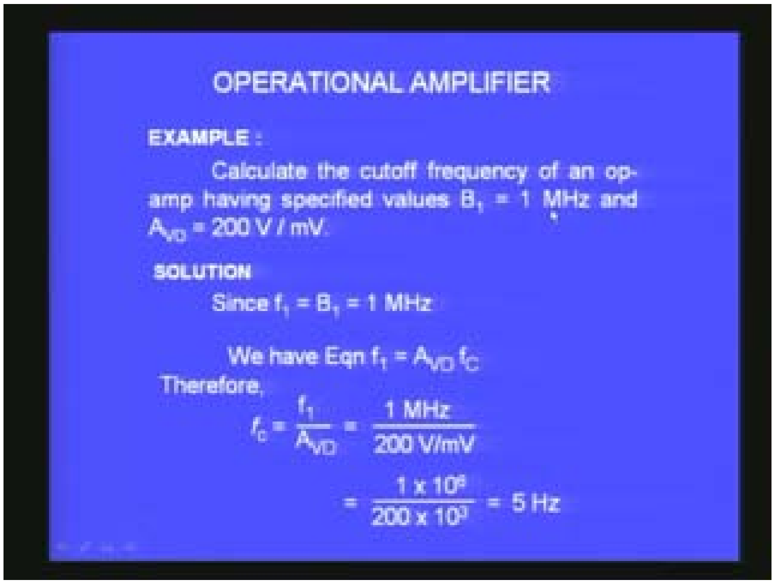

That means gain-bandwidth product is 1 mega hertz and the differential gain is given as 200 volts per millivolt. That means if I apply 1 millivolt at the input I will get 200 volts at the output. That is the gain factor. This is not true in reality. There is a maximum with reference to +12 and -12 volts. But this is an expression of the gain ratio. That is all. We know now that the gain-bandwidth product is 1 mega hertz and they have given the gain as 200 volt divided by millivolt and the cut off frequency is nothing but the gain-bandwidth product divided by the gain and in this case 1 mega hertz is the product divided by 200 volts divided by millivolts; that millivolts will become 10 power 3 when it goes to the numerator. It comes to 5 hertz. This corresponds to a large gain; 2 into 10 power 5 and 2 into 10 power 5 is the gain factor in this case and the bandwidth will be very, very small. When the gain is very large the bandwidth should be very, very small and the bandwidth is only 5 hertz. This is a typical example to show you that when I have a large gain, the bandwidth will become very, very small.

I want to show you a demonstration with two circuits having two different gains and we will try to find out how the bandwidth is changing when I increase the gain. That is what I wanted to show you. The first circuit has got 10K and 10K. These are all inverting amplifiers.

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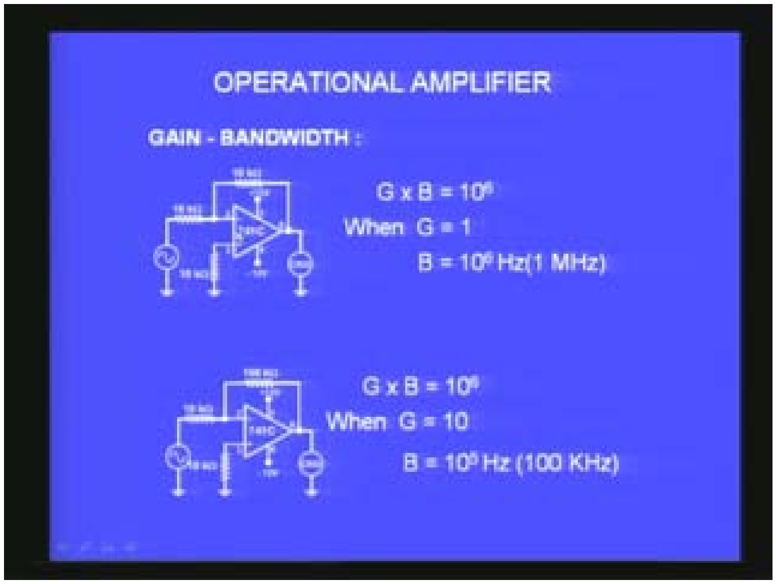

You have R_f and R_i; both are 10 kilo ohms and the pin number 3 is grounded. There is no input; 10K may compensate for the input bias current variations about which we have already seen. The output is seen on an oscilloscope and the input is from a signal source sine wave oscillator whose frequency can be varied up to several mega hertz. If the operational amplifier has got the gain-bandwidth product of 10 power 6 I assume, G the gain into the bandwidth is equal to 10 power 6. The 10K and 10K, the ratio of R_f by R_i is 1 and the gain is 1 for this circuit. When the gain is 1 the bandwidth B is 10 power 6 hertz. Till I go to nearly 1 mega hertz the output amplitude will not change. It will almost remain constant. In the second circuit what I have done is in the feedback instead of using 10 kilo ohm we have used 100 kilo ohm. What is the gain? In this case it is 100 divided by 10 which is 10. The gain is now increased by 1 order of magnitude from unity to 10. When the gain is 10 then the bandwidth becomes 10 power 5 hertz. That corresponds to 100 kilo hertz. Previously for the unity gain the bandwidth was 10 power 6. When I increase the gain by 1 order the bandwidth decreases by the same 1 order and it becomes 10 power 6 instead of 10 power 5 hertz. This will clearly bring out that the gain-bandwidth product is a constant. You can also try in the lab by increasing the gain to 100 and then you would find it corresponds to 10 power 4; you can keep trying that.

But if you have very large gain it becomes very difficult to stabilize the amplifier due to several other noise inputs. It is always advisable not to go beyond 100, the gain of the amplifier. How do you lower the gain? The only way you can lower the gain is by giving feedback and that is negative feedback. You have lot of good things happening to the amplifier when you give negative feedback. The input resistance increases, the output resistance decreases, the bandwidth increases, distortion decreases, etc and they are all by the value of gain that you have sacrificed. Instead of 10 power 6 which is the open loop gain if I do only 10 I have sacrificed a factor of nearly 10 power 5 and all the characteristics of the amplifier improve by a factor 10 power 5 and in that sense also one should not design amplifiers which are having very, very large gain. Then it will become very difficult to handle.

With this let me go to the table and show you a demonstration of the two amplifiers one with a gain unity and another with a gain of 10. I will apply the signal and try to observe what happens to the output? I will show you that the output starts increasing at a particular frequency. I will almost take that as nearly the cutoff frequency. Otherwise one has to carefully look at the output and calculate when it becomes 0.74 times the mid frequency gain and that will be the point to precisely choose. In general what we will do is we will take lot of data in the lab and then draw a graph in the log log plot and you will try to find out exactly the location where the value of the gain becomes 0.7 times the mid frequency gain. Here I will indicate to you qualitatively that beyond that f_c the amplitude starts coming down. That will help you to identify the bandwidth of the two amplifiers.

We have again the bread board with the two circuits simultaneously shown. This circuit has got a 10K in the feedback and 10K at the input. R_f by R_i is equal to 1.

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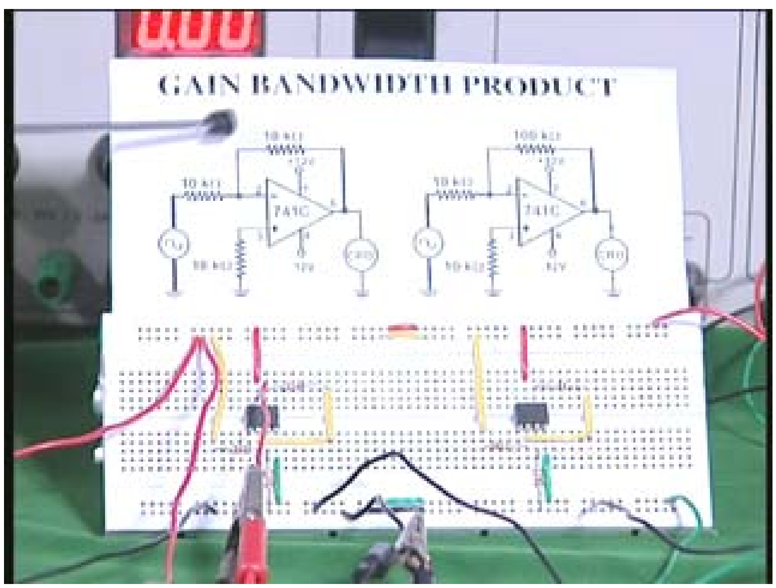

This is a inverting amplifier with a gain of 1 and that circuit is shown here at the bottom in the bread board and the input is connected from the signal generator which is again a sine wave oscillator. You have the amplitude variation here and you have the frequency variation here.

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You have got frequency multipliers here and I have use the sine input here. This signal generator is connected to the input and the output is connected to an oscilloscope which you can see here and it is dual trace oscilloscope. The top one is corresponding to the input and the bottom one is corresponding to the output. The two are connected here. Now what I am going to do is I am going to vary the frequency of the input. I am going to vary this knob the frequency of the input and observe the oscilloscope output carefully. When I keep increasing you can see the frequency increasing but the amplitude of the output is almost a constant. The amplitude of the output is constant; both the input and output is constant till I complete the entire range of frequencies using this knob.

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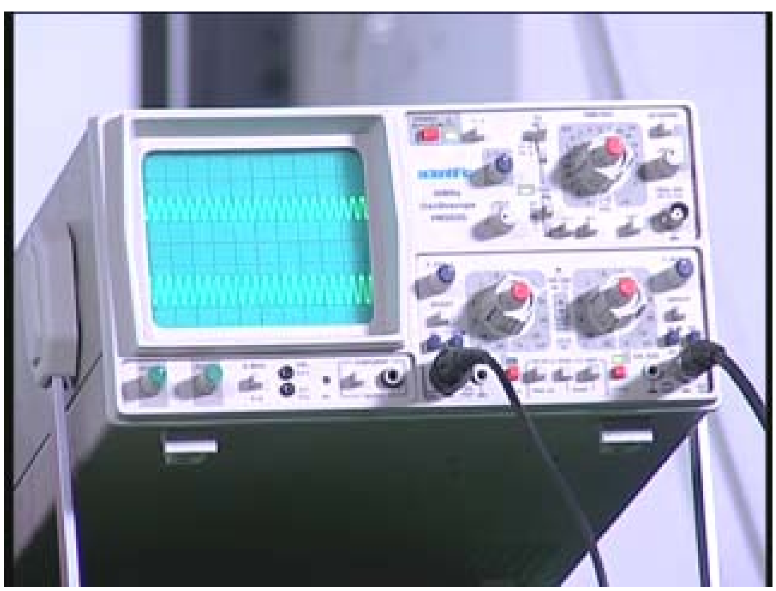

I have almost come to the end of this and the frequency also has increased. Now I will go to the next multiplier. I will bring down to the original value; now it is in 10K. I go into 100K. I have pressed the 100K. The two signals are very close. Let me increase the sweep frequency so that I am able to see few of the wave forms and now I am going to again increase in 100 kilo hertz range the input frequency.

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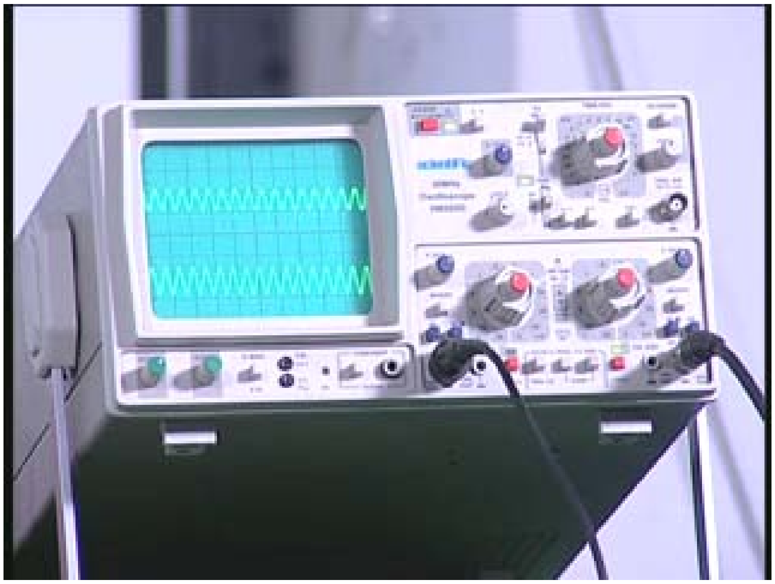

It starts decreasing slowly when I am almost at 300 kilo hertz. If I now go to higher frequency like 1 mega hertz the output is decreased in amplitude.

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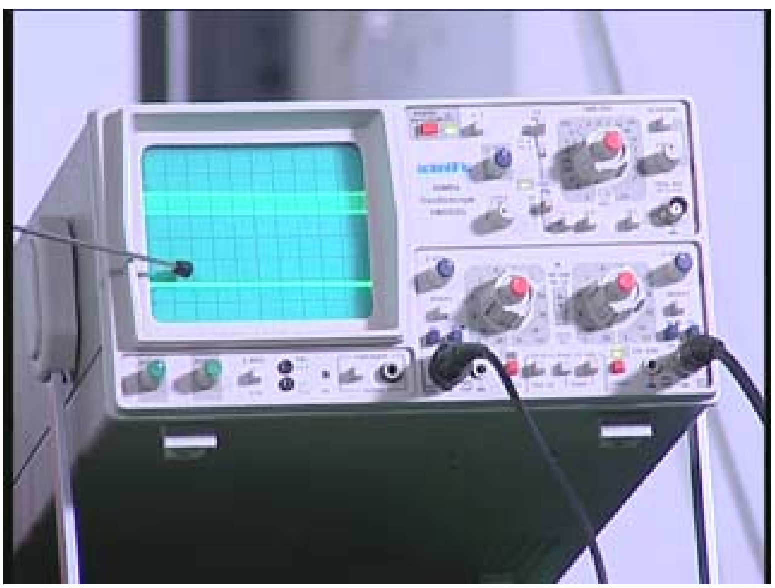

When this decrease starts is what we should worry about. This is minimum around 200 and is already less compared to the input, less than what you had previously. Because the gain is 1 they must have the same amplitude in principle. But the bottom signal is having lower amplitude than the top and this happens when I press and go into the 1 mega hertz. Several other hundreds of kilo hertz away it starts decreasing and we can precisely calculate from the amplitude when it becomes 0.7 and it will be very close to 1 mega hertz because the gain-bandwidth product for the 741 is very close to 10 power 6. This is corresponding to the gain of 1 in the circuit that I have shown. This is the circuit that I have now used with a gain a 1.

I am going to connect the other amplifier now. It is around 5 kilo hertz range and in the oscilloscope you see the two amplitudes. If you look at this dials they will be 10 times. This will be around 0.5; this will be around 5. There is a gain of 10 shown. The amplitude here is almost equal because the amplification factor using the knob has been kept 10 times.

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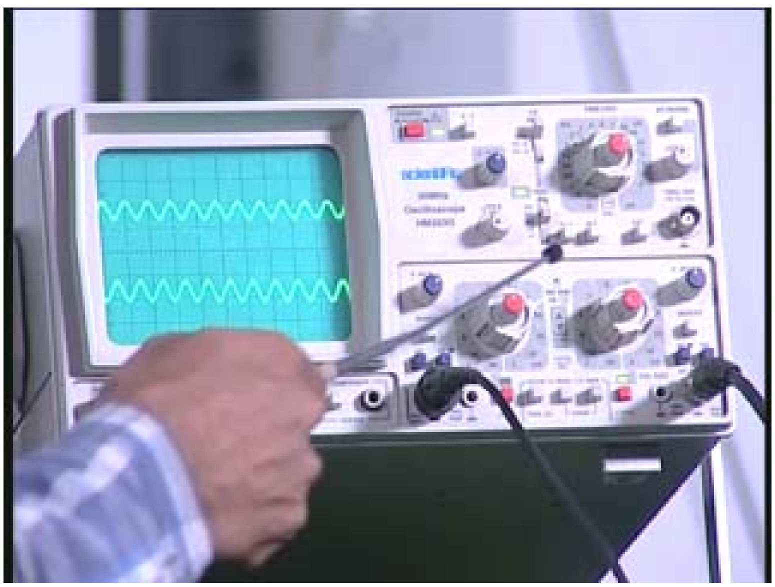

That takes the care of the 10 because here in the feedback I have used 100K and 100K divided by 10K gives me a factor of 10. That is the gain of this amplifier. The same amplifier is shown here expect that this resistance which was previously 10K now I have changed to 100K. The two inputs are given as usual and let me now vary the frequency and see how the amplitude is changing. I am changing now in 10 kilo. When I go through the entire range there is no significant change in the amplitude of both. I will again change the sweep to see few waves. I am going up to the extreme end of the knob. There is not much of a change in the amplitude. I will increase the frequency multiplier to 100K range. I am going to increase in 100K range. As soon as I do that the gain starts decreasing. The gain here has started decreasing. It is nearly 1 division on the screen.

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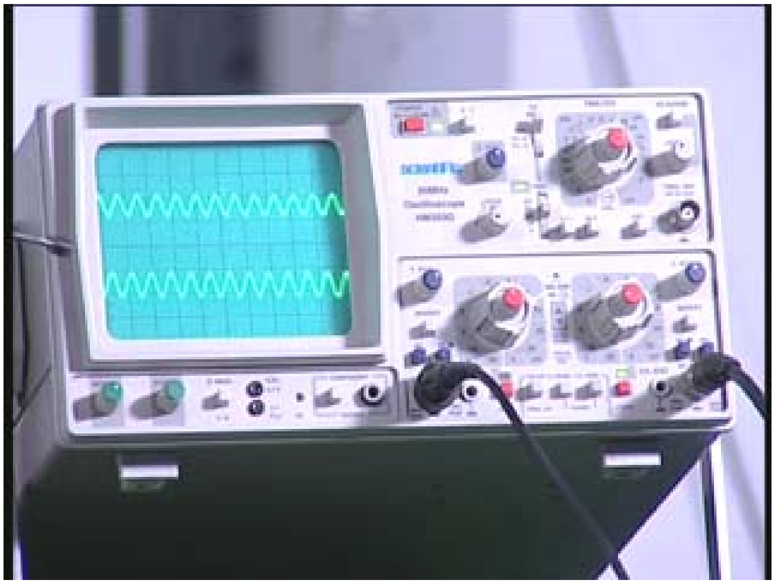

Now as I increase the frequency the amplitude starts decreasing.

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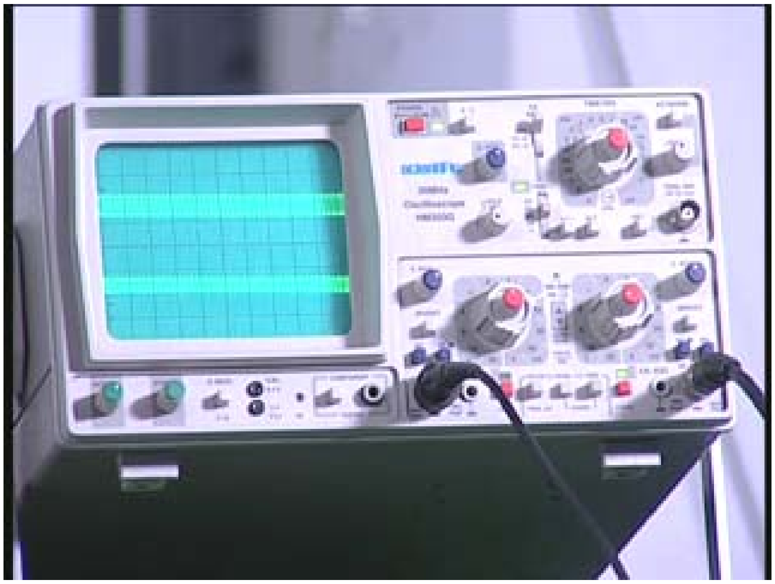

This corresponds to the cut off very close to the cut off and this comes in the 100 kilo hertz range nearly about 200 kilo hertz. Previously it was coming when I used the gain of 1. Till 700, 800K you had no fall in the gain but now you do get a gain at much lower frequency and the gain-bandwidth product makes (or) shows that when you increase the gain the bandwidth decreases. The bandwidth in this case has decreased. We can continue and try to do for a gain of 100. Then you must make sure that amplitude of the output will be very, very large. You should correspondingly reduce the input signal so that you can still have reasonable amplitudes of the two signals on the oscilloscope. I leave that for you to try on your known.

We have seen a demo of the gain-bandwidth product; how it is a constant for two situations where one you have an amplifier with the gain of unity and when you look at the exact cut off corresponding to this amplifier that will give you the gain-bandwidth product. Then we also choose another amplifier with a gain of 10 and then we looked at the bandwidth. Even when I come to nearly 100 kilo hertz the gain starts falling. That means output amplitude starts decreasing. That corresponds to the gain falling and that shows that the gain-bandwidth product is a constant.

Now we go to the last of the characteristic which is called as slew rate. Slew rate is a very important characteristic especially when you want to look at large amplitude signals at the input.

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When you give a large amplitude signal you expect the output signal also should be quickly changing but you would find it is not happening that way. So a factor or a characteristic of the amplifier which identifies this variation how fast the output changes with reference to time corresponding to the input change is what is known as slew rate, SR. Slew rate is defined as the maximum rate at which the amplifier output can change in volts per micro second. The unit is generally volts per micro second. Slew rate is delta V_0 that is the change in the output voltage divided by delta t where delta t is measured in micro seconds. Delta V_0 is measured in volts. This provides how fast the output can vary corresponding to the input change. One way to look at is to look at a step input. I have shown in the graph for example I give suddenly a 1 volt jump at the input. The input goes from 0 to 1 volt and what happens to the output? In principle you expect the output also should go from 0 to 1 volt immediately.

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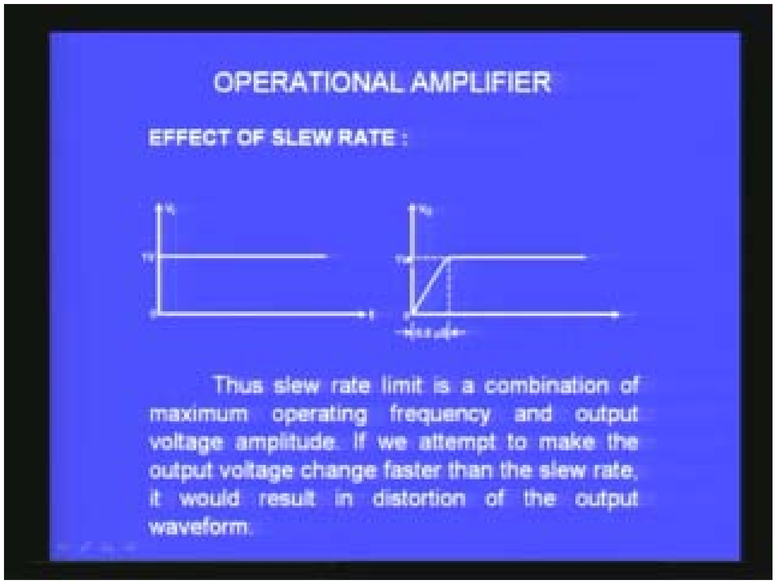

There is nothing like immediately. The output will take some time to react to the input and that time is what will be decided by the slew rate of the amplifier. Here this is corresponding to the input this is corresponding to the output. When the input goes from 0 to 1 volt the output goes not immediately but with a finite slope to the value 1 volt. The x-axis is in micro second time and y-axis in volts. This 1 volt divided by this time which is here 0.5 micro second gives me the slew rate of the amplifier. That is the way we can measure. I will again explain to you with a actual square wave.

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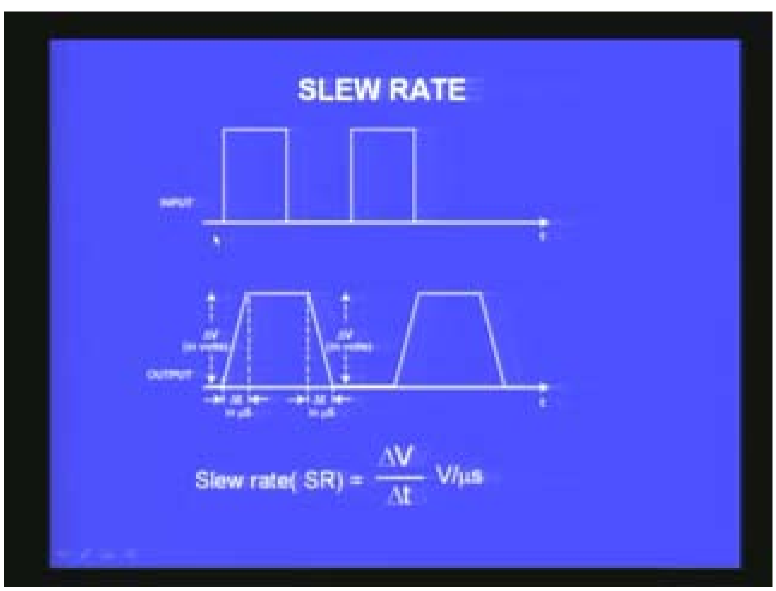

If I give a large amplitude square wave 1 volt or 2 volts and look at the output, the output will show a finite slope and if I now look at how much is the variation in the amplitude at the output variation and look at the time it takes for this value to reach the maximum and divide one by the other I will get the slew rate; delta V by delta t where delta V is in volts and delta t in micro second gives me the slew rate. It is a very simple way of measuring slew rate and I will give an example, numerical example for an op amp having a slew rate of 2 volts per micro seconds. This is a very typical value of the slew rate for many of the operational amplifiers.

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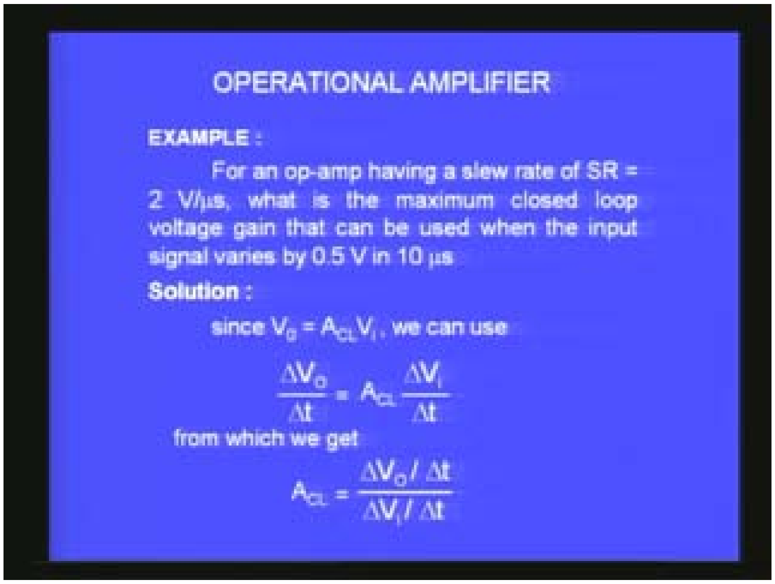

What is the maximum closed loop voltage gain that can be used when the input signal is 0.5 volts in 10 micro seconds? This slew rate can introduce a restriction on the gain that I can have. Not only the bandwidth because slew rate also is indirectly related to the bandwidth and the rise time. V_0 is equal to A closed loop multiplied by V_i. Differentiating both sides delta V_0 by delta t is equal to A_{CL} into delta V_i by delta t. A_{CL} closed loop gain can be taken as delta V_0 by delta t by delta V_i by delta t. Delta V_0 by delta t is what we call the slew rate and this is slew rate divided by delta V_i divided by delta t. In the problem they have said it is 0.5 volts per 10 micro second at the input.

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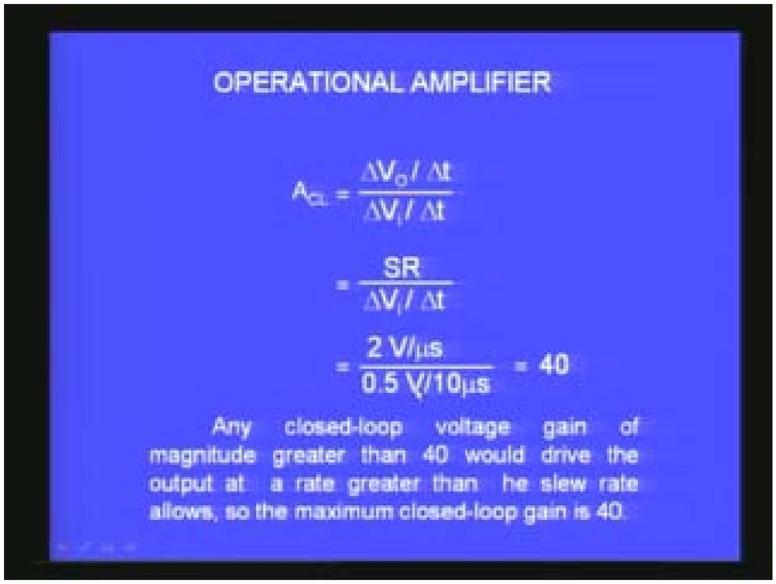

I put it at the denominator. 2 volts per micro second is the slew rate. I put it at the numerator and if you calculate this the gain is 40. That means I cannot design using this operational amplifier which has got a slew rate of 2 volts per micro second any gain greater than 40. That is what it means. Therefore this puts a restriction on the gain that I can achieve for a given amplitude of the input voltage. If you want to measure the slew rate of operational amplifier it's a very simple circuit I have shown on the screen.

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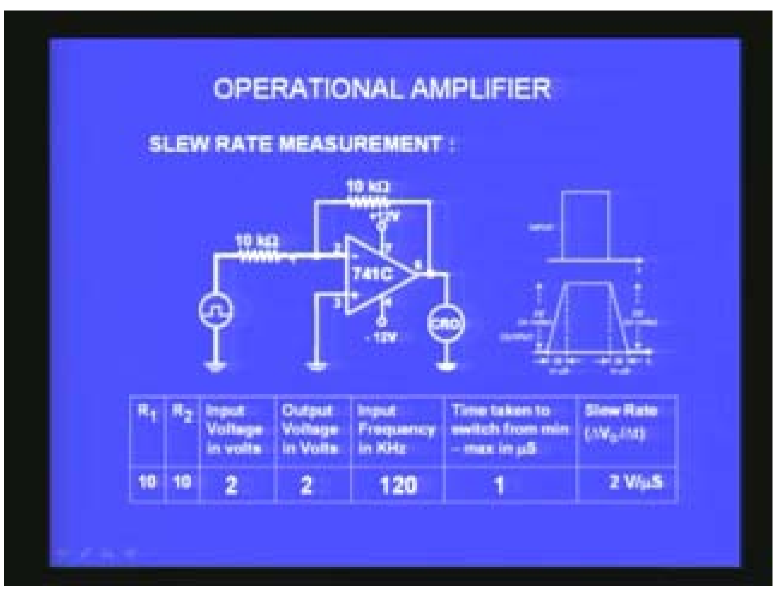

You have a gain 1 amplifier; 10K and 10K. It's an inverting amplifier. I give a square wave and at the output I will get a distorted square wave with some finite slope and I will calculate directly from the oscilloscope what is the time corresponding to this delta t and the amplitude. If I divide one by the other I will get the slew rate. I have given a small example here. R_1 and R_2 are 10K each. These are all in kilo ohms and input voltage is around 2 volts. Output voltage also is 2 volts because the gain is 1 and input frequency is around 120 kilo hertz and time taken to switch from minimum to maximum is 1 micro second this is delta t and the slew rate is 2 volts divided by 1 micro second that it is 2 volt per micro second is the slew rate.

Now I will show you a demo of this slew rate. I have the same circuit here with the two resistors both of them equal to 10 kilo ohm.

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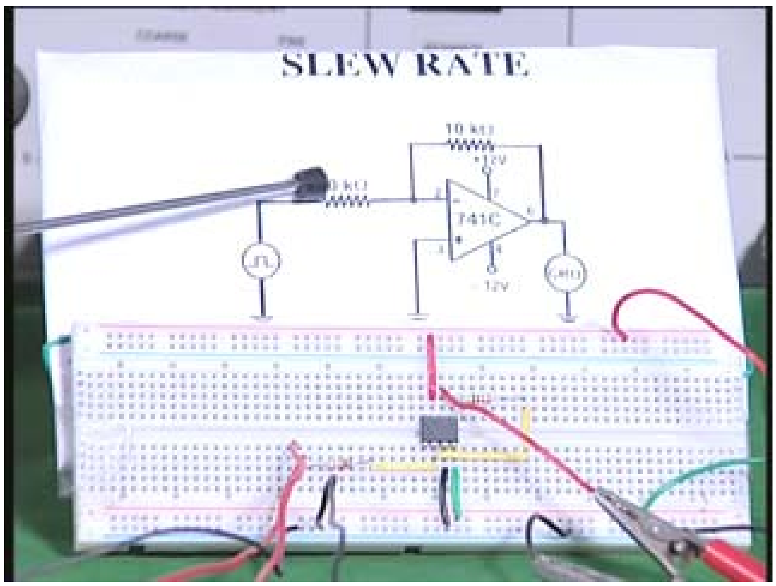

It is a unity gain inverting amplifier. I have got an input and that is now in square wave in this sine wave function generator. I have pressed the square wave knob and it is giving out square wave. It is around 26 kilo hertz; the frequency corresponding to this knob and now what is the output? You can see on the oscilloscope this is the input square wave. There the vertical line is almost not seen because it is at the input whereas because of the slew rate at the output there is a finite slope. You can see the sloping lines.

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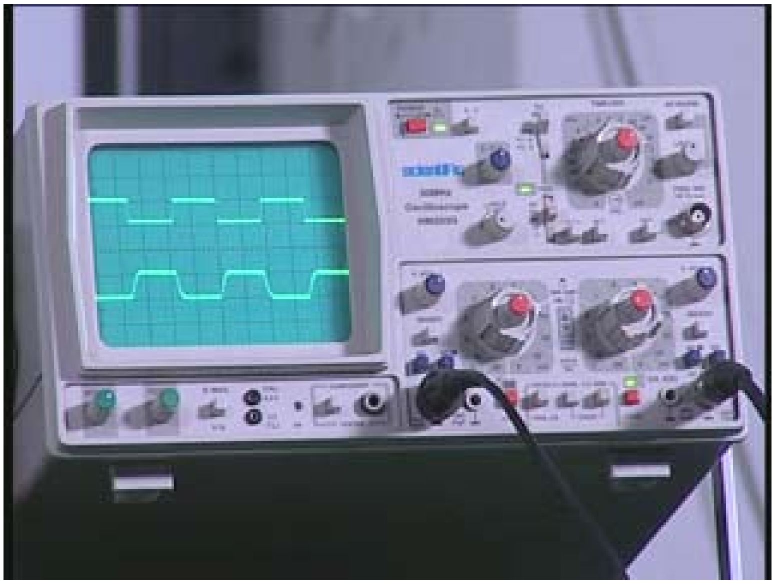

If I now increase the gain you will able to see the variation much better. This is not instantaneously going to high but with a finite slope.

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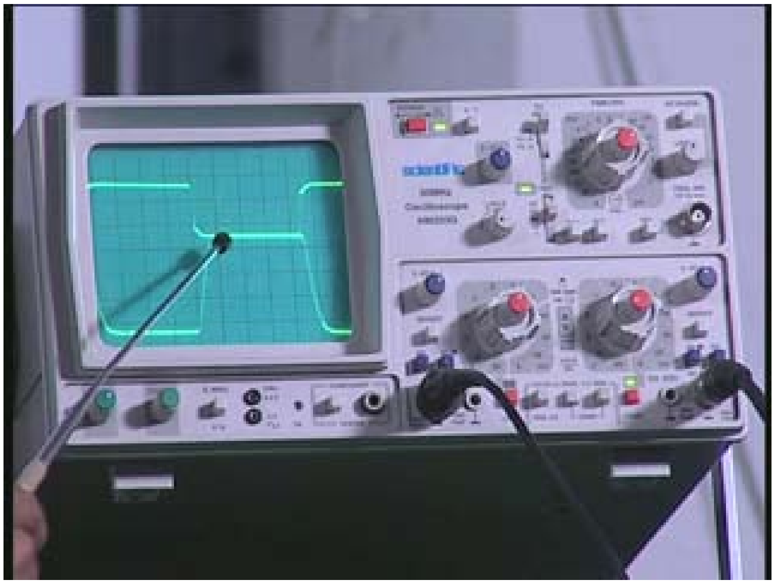

I calculate the gap here from the micro second that I can read from here and from the amplifier gain factor I can find out the amplitude here. Divide the amplitude by this delta t which is read from the oscilloscope you can get the slew rate and in this case if you actually take a close look at this it comes to around 2 micro second. This corresponds to the slew rate of the operational amplifier. We also saw a demonstration of how to measure the slew rate of an operational amplifier by taking an example of a unity gain amplifier. I give a square wave and monitor the square wave using the oscilloscope at the output and calculate from the slope the slew rate.

So far what we have done is we have listed the different characteristics of the operational amplifier and we have discussed the basic definition of the characteristics and we have also seen how we can measure these characteristics in the actual laboratory. I want you to recapitulate; you have the input offset voltage, input bias current, input resistance, output resistance, common mode rejection ratio, the transfer characteristics between the input output of the amplifier, the gain-band width product of the operational amplifier and the slew rate. All these characteristics are the most important characteristics of the operational amplifier. One should have a good idea about these amplifiers if you want to make use of these operational amplifiers for different application purposes.

For example when I want to amplify some small currents I must make sure the input bias current of the operational amplifier itself is not close to the current that I want to measure in a current to voltage converter configuration. I must make sure that the input bias current is at least $1/10^{th}$ or even lower than the order of magnitude of the current that I want to measure. Similarly when I want input voltages which are in microvolts I must make sure the offset voltages of the operational amplifier are much lower than that. It should be nano or pico volts range and I must make a careful selection of the operational amplifier whose input offset voltage and output offset voltage are very, very small compared to the order magnitude to the voltages that I would like to measure in my actual application. For such considerations it is very important that we have very clear idea about the different characteristics of the operational amplifier and how one can measure them in the actual laboratory.

In the next lecture we will take up some application circuits of the operational amplifiers. We have seen about the negative feedback and the various configurations of the negative feedback and then we have discussed about the mathematical operations that can be performed with the operational amplifier and we have also seen the different characteristics of the operational amplifier. Now we are ready to go into different application circuits of the operational amplifier. Thank you!