Basic Electronics
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Lecture – 54
Sinusoidal oscillators (continued)

Welcome back to Basic Electronics. In this lecture, we will continue with sinusoidal oscillators; and look at how the output amplitude can be controlled using a gain limiting network. After that, we will consider an important limitation of amplifier circuits, which we have not addressed so far, and that is frequency response. We will first look at the frequency response of an inverting amplifier for different gain values; we will then explain this frequency response with a realistic model of the op-amp. Let us get started.

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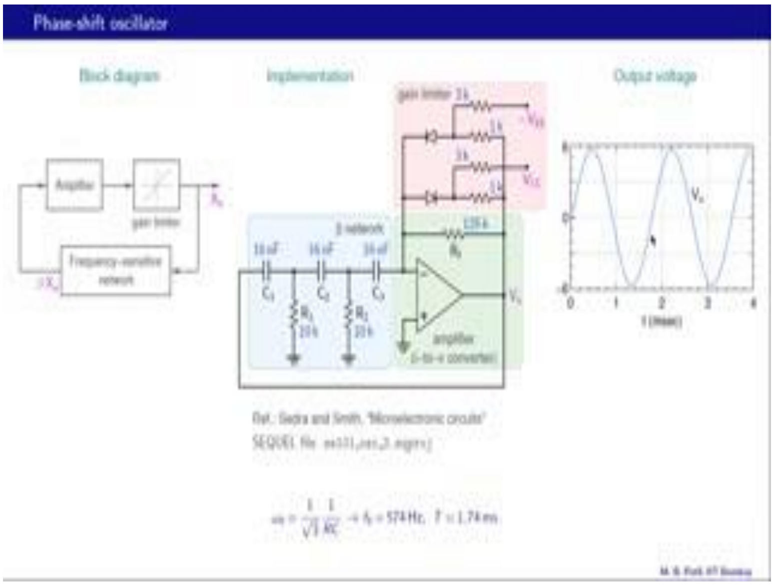

Ref.: Sedra and Smith, "Microelectronic circuits"

$\omega_0 = \frac{1}{\sqrt{3}}\frac{1}{RC} \rightarrow f_0 = 574$ Hz, $T = 1.74$ ms

So, here is our complete implementation. And let us first relate the implementation with our block diagram. What is X o in the implementation that is of course V o, what about x f which is beta times X o. X f in this case is this current here not shown, but as we discussed in the last slide X f in this case is not a voltage, but it is a current. What is our A, our A is not a voltage to voltage gain, but it is a voltage it is a current to voltage gain and that to be found to be equal to minus R f. Now, for this beta network we found that omega 0 would be 1 over square root 3 1 over R c and that gave us f 0 equal to 574 hertz and we have already done that calculation previously just repeating it here. And our R f, we found in the last slide should be equal to 12 times R, R here is 10 k. So, twelve times 10 k is 120 k, and we make it slightly larger than 120 k, so that is how we get this 125 k and that is done as we mentioned earlier to make sure that the circuit does oscillate on power up.

This is the gain limiter block. And we have seen this circuit earlier, if you recall. Let us see how it works. We have seen that the gain of this amplifier is minus R f. Now, when this voltage is small these diodes are off, and the only resistance then is R f, so the gain is large. When this voltage increases either in the positive direction or in the negative direction one of these diodes turns on and then this net resistance decreases and that is how the gain decreases as the voltage increases, so that is how gain limiting is achieved.

Here is the output voltage obtained by simulation. And the circuit file is specified here, you can try out the simulation as well. And let us check whether it shows the correct frequency. The frequency of oscillation that we expect is f 0 equal to 574 hertz and that gives us a period T equal to 1 by f 0 equal to 1.74 milliseconds. And we see that in 1.74 milliseconds somewhere here, we do have 1 cycle, and therefore the result seems to be correct.

Now, the question that arises is can we do something about this amplitude, the answer in this case is yes, we can play with these parameters here, and use those to change the amplitude of the output voltage. And let us see how that can be done.

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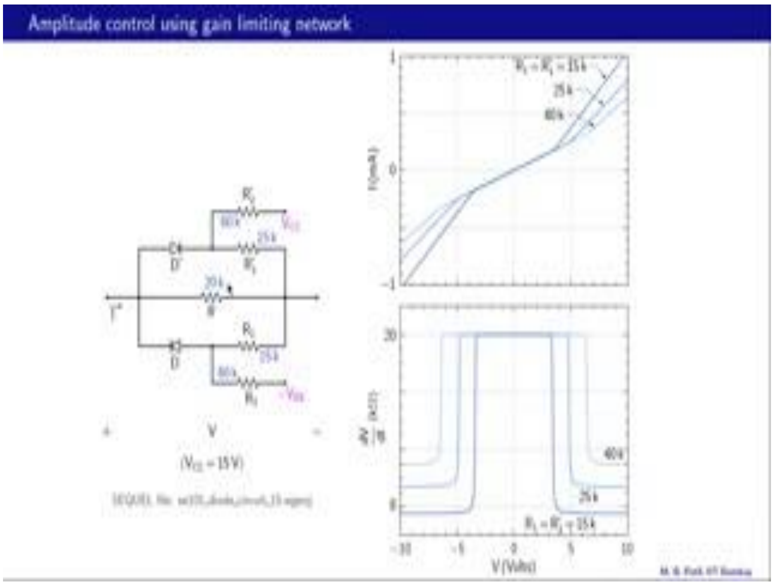

Amplitude control using gain limiting network

Here is the gain limiting network that we used in the phase shift oscillator. The values are a little different but not very important. And if you recall we have seen this circuit earlier with these values 60 k, 16 k and 20 k and in that situation we had obtained I versus V given by this dark curve here and d V d I where V is this voltage and I is this current was given by this curve here. So, in this region of the voltage, the resistance is constant and then on either side it starts dropping because one of these diodes starts conducting; or our gain limiting happens when this resistance falls here.

Let us now connect this picture with the amplifier that we saw in the phase shift oscillator in the last slide. And if you recall the gain was proportional to minus R f. So, when the resistance is high the gain is high; and when the resistance drops the gain becomes slow. In other words, the gain is constant in this region; and outside it drops and that is what causes amplitude limiting. Now, if we increase the width of this region then we will also increase the amplitude, so that is the basic idea behind amplitude control here.

How can we change the width of this region, there are different ways of doing it. We can change R 1 and R 1 prime together or we can change R 2 and R 2 prime together or we can change this power supplier. Of course, the last option is not very practical because we do not want to change the power supply values. What we have done here in this plot is we have changed R 1 and also R 1 prime. This is the plot for 15 k the dark one as we have seen already. The next plot is for 25 k; that means, this resistance is 25 k, this one is also 25 k and the one after that is for 40 k.

As we change the resistance value, we notice that the breakpoint also shifts. Here is the break point for 15 k; for 25 k it is here, and for 40 k it is here. It can be more clearly seen in this bottom picture that is the break point for 15 k; for 25 k it is here and for 40 k it is here. So, if we change the resistance from 15 k to 40 k, what it means is that the amplitude will change from about this much to about that much. And let us check that out now with the help of simulation in the next slide.

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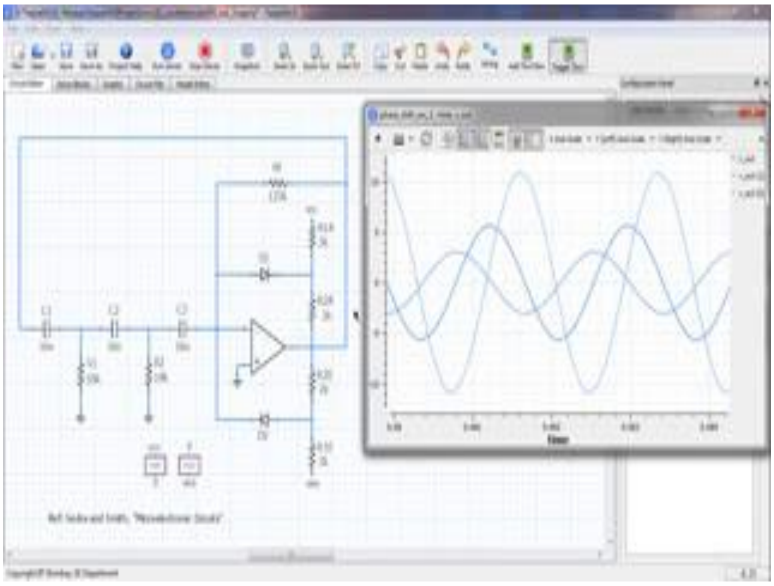

Let us now look at the simulation results for the phase shift oscillator. The component values here R and C and R f are the same as what we had in the last slide. So, the frequency of oscillation is expected to be the same namely 574 hertz and that corresponds to a time period of 1.74 milliseconds if you recall. What we have done here is change this resistance and that means that we also change this resistance and the output voltage is plotted for three different values of the resistance. This waveform corresponds to a resistance of 0.5 k, this one 21 k, and this one 22 k, and the amplitude control can be clearly observed.

The frequency of oscillation of course, does not change and we can check that out we can identify the peaks, for example, this one and this one, see the difference between these two peaks and that should turn out to be 1.74 milliseconds and that will be also true about the other waveforms. So, we can take the difference between this and that or that and that and all of these will turn out to be 1.74 milliseconds. Now, one comment about the phase of these waveforms, the phase is different for each of them, but the phase is not particularly relevant here and we can just ignore it.

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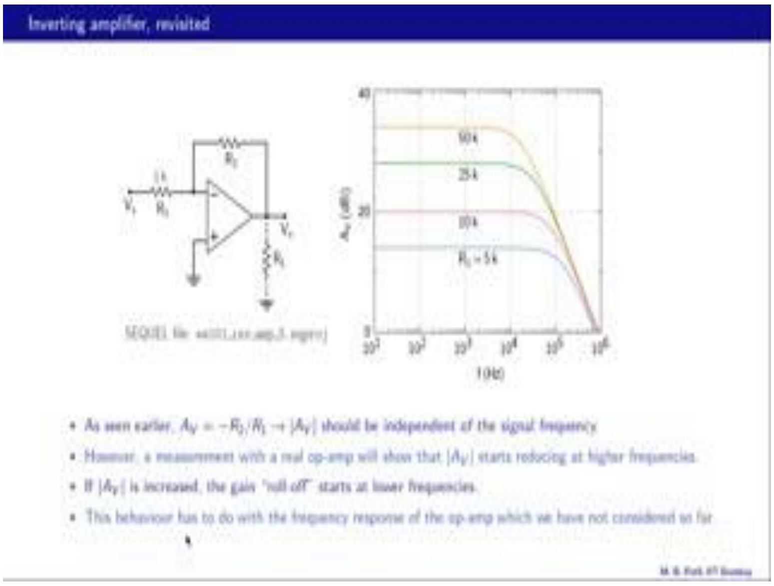

Inverting amplifier, revisited

- As seen earlier, $A_V = -R_2/R_1 \rightarrow |A_V|$ should be independent of the signal frequency.
- However, a measurement with a real op-amp will show that $|A_V|$ starts reducing at higher frequencies.
- If $|A_V|$ is increased, the gain "roll-off" starts at lower frequencies.
- This behaviour has to do with the frequency response of the op-amp which we have not considered so far.

Let us now revisit the inverting amplifier, which we have seen earlier; and discuss a very important topic, which we have not touched upon so far. So, here is an inverting amplifier circuit with R 1 equal to 1 k. And we are going to change R 2, consider different values of R 2 and that is why we have not specified the value here. As we have seen earlier, the voltage gain for this amplifier is minus R 2 by R 1. And we expect the gain to be independent of the signal frequency, but that does not happen in real life. The measurement with a real op-amp shows that the gains starts reducing at higher frequencies and let us see how. Here is a plot of the gain in d B versus frequency in hertz where the frequency is plotted on a log scale. And we consider various values of R 2 - 5 k, 10 k, 25 k, and 50 k. Let us look at the R 2 equal to 5 k curve, what is the gain for this R 2 it is R 2 by R 1. So, 5 k by 1 k or 5 we have to convert that to d B of course, and that gives us this value here.

Now, the important point to observe is that the gain is constant for much of this frequency range all the way up to say 10 kilo hertz or little higher than that, but at some point it starts falling and this fall is called the roll-off the gain with frequency. What happens if we change R 2 from 5 k to 10 k, the gain doubles and we have a higher gain here, but also the roll-off of the gain with frequency starts happening at a lower frequency. Now, for 5 k it happened here; for 10 k it is happening here; and for 50 k its happening at an even lower frequency, so that is a very important point to observe and it has of course, important practical implications as well. So, if the gain is increased the gain roll-off starts at lower frequencies. And this behavior has to do with the frequency response of the op-amp which we have not considered so far. So, let us look at it now.

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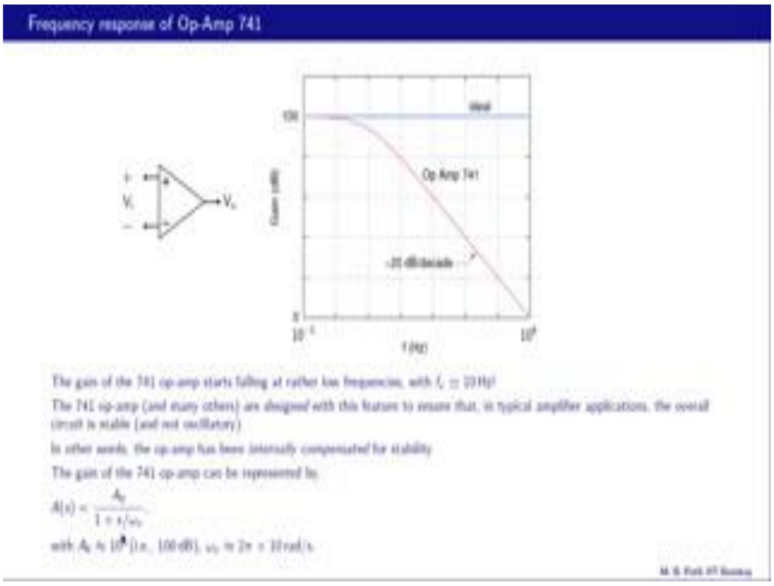

Frequency response of Op-Amp 741

The gain of the 741 op-amp starts falling at rather low frequencies, with $f_c \simeq 10\,\text{Hz}$!

The 741 op-amp (and many others) are designed with this feature to ensure that, in typical amplifier applications, the overall circuit is stable (and not oscillatory).

In other words, the op-amp has been internally compensated for stability.

The gain of the 741 op-amp can be represented by,

$$A(s) = \frac{A_0}{1 + s/\omega_0}$$

with $A_0 \approx 10^5$ (i.e., 100 dB), $\omega_0 \approx 2\pi \times 10\,\text{rad/s}$.

Let us start with the frequency response of the op-amp; in particular op-amp 741 here is the gain in dB versus frequency in hertz and we are plotting the frequency on log scale going from 0.1 hertz all the way up to 1 mega hertz here. So, it is 0.1 hertz, 1 hertz, 10 hertz 100 hertz and so on. Now the ideal response of the op-amp 741 would be flat that is it would be independent of the frequency, but this is what the real response looks like it starts dropping off at some frequency here and then it reduces at the rate of minus 20 dB per decade. And if we join this asymptote with this one, they intersect at about 10 hertz. So, what it means is that the gain of the 741 op-amp starts falling at rather low frequencies with a cutoff frequency or 3 dB frequency of only 10 hertz.

And this may come as a surprise, but this fall off at 10 hertz is not accidental the 741 op-amp and many others in fact, are designed with this feature that is a fall off at a relatively low frequency like 10 hertz. And that is done to ensure that in typical amplifier applications, the overall circuit is stable and not oscillatory. In other words, the op-amp has been internally compensated for stability. And you will learn more about stability of amplifiers in an advanced analog circuits course. For now, it suffices to know what the op-amp 741 frequency response is like; and with that in mind we will now try to understand the frequency response of the inverting amplifier which we saw in the last slide.

The frequency response of the 741 op-amp can be represented by this equation here A of s or j omega equal to A 0 divided by 1 plus s by omega c. And it is easy to figure out where this is coming from. This is our frequency response. We have only one corner frequency somewhere here two asymptotes that one and that one; and this asymptote has a slope of minus 20 dB per decade. So, what it indicates is that there is only one single pole in this entire system. And therefore, A of s is equal to A 0 by 1 plus s by omega c. A 0 is the low frequency gain which is 100 dB, 100 dB corresponds to 10 raise to 5. So, A 0 is just a constant equal to 10 raise to 5; and omega c is the cutoff or corner frequency that is somewhere here; and in hertz, it is about 10 hertz in radians per second, it is 2 pi times 10 radians per second.

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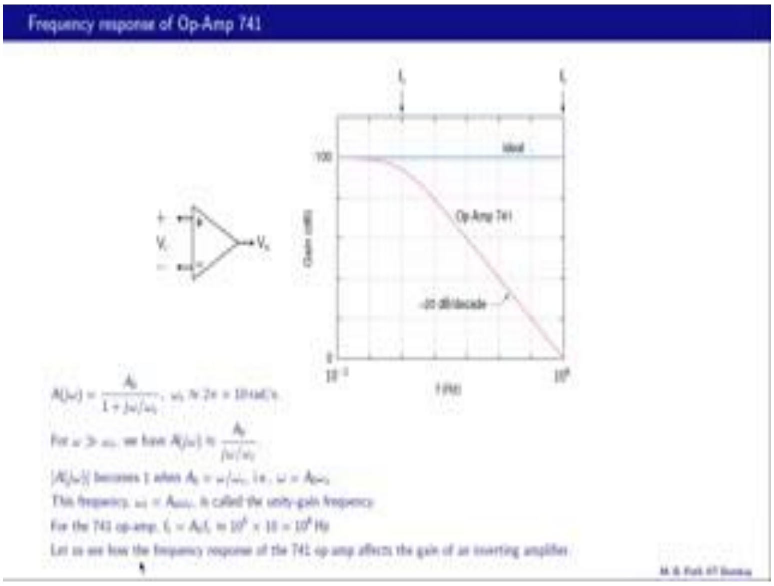

Frequency response of Op-Amp 741

$A(j\omega) = \frac{A_0}{1 + j\omega/\omega_c}$, $\omega_c \approx 2\pi \times 10$ rad/s

For $\omega \gg \omega_c$, we have $A(j\omega) \approx \frac{A_0}{j\omega/\omega_c}$

$|A(j\omega)|$ becomes 1 when $A_0 = \omega/\omega_c$, i.e., $\omega = A_0\omega_c$

This frequency, $\omega_t = A_0\omega_c$, is called the unity-gain frequency

For the 741 op-amp, $f_t = A_0 f_c = 10^5 \times 10 = 10^6$ Hz

Let us see how the frequency response of the 741 op-amp affects the gain of an inverting amplifier

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So, here is our A of j omega again, A 0 which is a constant divided by 1 plus j omega by omega c, where omega c is about 2 pi times 10 radians per second. Now, let us consider the case where omega is much larger than omega c so that means, we are away from this cutoff frequency say somewhere here. And in that case, this one is small and we get A of j omega equal to A 0 divided by j omega by omega c. And note that this quantity becomes 1, the magnitude of a of j omega becomes 1, when A 0 is equal to omega by omega c that is when omega becomes equal to A 0 times omega c. And this frequency omega equal to A naught times omega c is called the unity gain frequency; and it is denoted by omega with a subscript t. And for the 741 op-amp, the corresponding frequency in hertz which is denoted by f with a subscript t is A 0 times f c, where f c is this corner frequency or the 3 dB frequency that is 10 raise to 5 times 10, A 0 is 10 raise to 5 and f c is 10 hertz. So, that f t for the 741 op-amp turns out to be 10 raise to 6 hertz. So, that is our unity gain frequency for the 741 op-amp. So, f c is marked over here in the plot and f t is 10 raise to 6 hertz. Now, let us see how the frequency response of the 741 op-amp affects the gain of an inverting amplifier.

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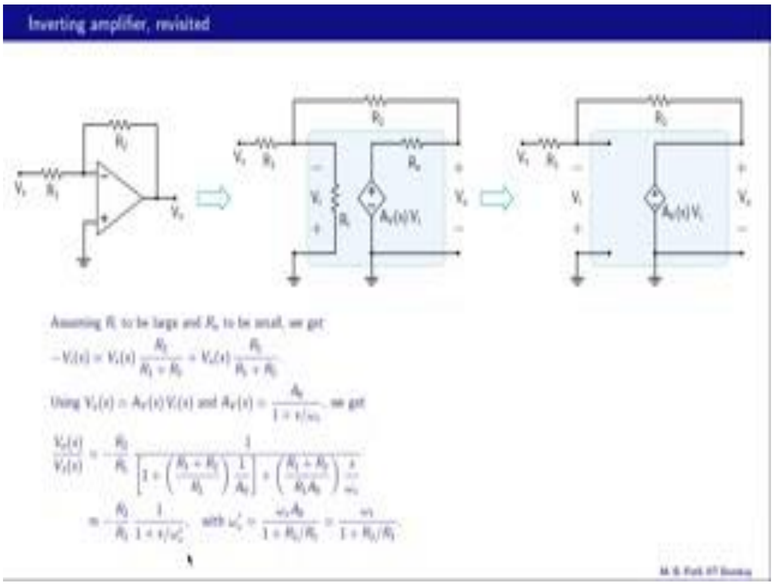

Inverting amplifier, revisited

Assuming R_i to be large and R_o to be small, we get

$$-V_i(s) = V_s(s)\,\frac{R_2}{R_1+R_2} + V_o(s)\,\frac{R_1}{R_1+R_2}$$

Using $V_o(s) = A_V(s)\,V_i(s)$ and $A_V(s) = \dfrac{A_0}{1+s/\omega_c}$, we get

$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{\left[1+\left(\dfrac{R_1+R_2}{R_1}\right)\dfrac{1}{A_0}\right]+\left(\dfrac{R_1+R_2}{R_1A_0}\right)\dfrac{s}{\omega_c}}$$

$$\approx -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'},\quad \text{with } \omega_c' = \frac{\omega_c A_0}{1+R_2/R_1} = \frac{\omega_t}{1+R_2/R_1}$$

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Here is our inverting amplifier and we want to understand its frequency response now which we have seen earlier. First, what we will do is replace the op-amp with its equivalent circuit model consisting of the input resistance R i, the output resistance R o and this gain element. We will assume that the input resistance is very large. So, that becomes an open circuit the output resistance is very small, so that is a short circuit, and that gives us this equivalent circuit over here. Open circuit here and a short circuit here. And now what we want to do is to get V o by V s as a function of frequency and that frequency dependent of course, will come from the frequency dependence of A V of the op-amp which is shown over here as A V of s.

So, let us start with the voltage at this node with respect to ground and we can obtain that by superposition. We have V s here and we have V o here with respect to ground. And using these two voltage sources, we can calculate the voltage at this node by superposition. And what is that node voltage that is minus V i with respect to ground. So, that gives us one equation like that. So, minus V i is equal to V s times R 2 by R 1 plus R 2 plus V o times R 1 by R 1 plus R 2; and this part we have got using superposition.

Now, let us use the fact and that V o is a V times V i, this voltage is a V times V i. And we also know the frequency dependence for the op-amp gain that is A V of s equal to A 0 divided by 1 plus s by omega c. So, using these two and putting these back here we get the following relationship between V o and V s minus R 2 by R 1, 1 divided by all of this and you are definitely encouraged to derive this equation yourself. Now, this term is small because A 0 is a large number 10 raise to 5.

And therefore, we can ignore this term with respect to this 1 here. And now we can rewrite the gain of the inverting amplifier V o by V s this one as minus R 2 by R 1 times 1 divided by 1 plus s over omega c prime. Now, this expression here is the same as this term; and omega c prime is omega c times A 0 divided by 1 plus R 2 by R 1. Now, omega c times A 0 we have seen before and that is denoted by omega t that is the unity gain frequency of the op-amp. And for op-amp 741 as we have seen earlier, it is 2 pi times 10 is to 6 radians per second. So, now, we know the gain of the inverting amplifier as a function of frequency, this expression here; and we can now proceed and plot the gain versus frequency for different values of R 2.

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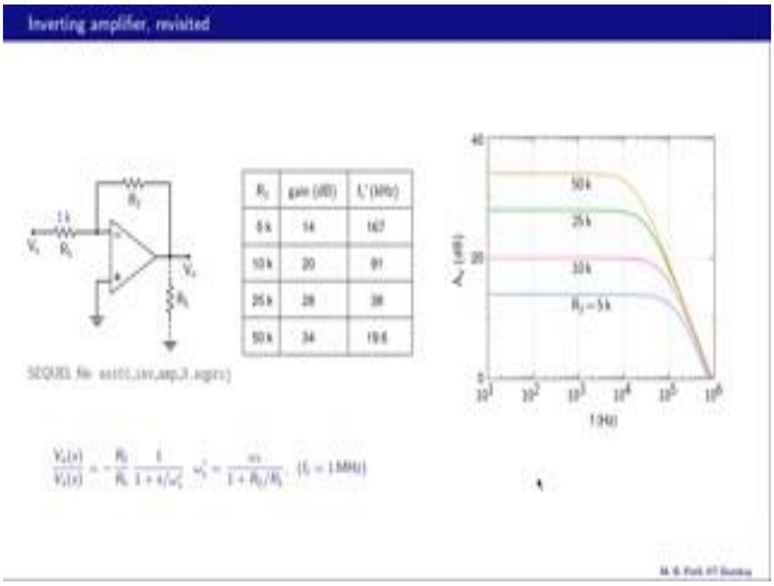

Inverting amplifier, revisited

R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91
25 k	28	38
50 k	34	19.6

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$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'},\quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}\quad (f_t = 1\,\text{MHz})$$

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So, here is the gain expression again V o by V s minus R 2 by R 1 times 1 by 1 plus s by omega c prime. So, just a single pole, where omega c prime is omega t divided by 1 plus R 2 by R 1; and omega t is 2 pi times f t, where f t is one megahertz for the 741 op-amp. So, now what we will do is prepare this table, and also plot the gain as a function of frequency for various values of R 2. For each R 2, we will note down the gain the low frequency gain which is given by R 2 by R 1, and also the corner frequency or the 3 dB frequencies which is f c prime the same as omega c prime by 2 pi.

With R 2 equal to 5 k, the gain is 5 k by 1 k or 5, and that is 4 dB; and the corner frequency f c prime is f t divided by 1 plus R 2 by R 1, so that is 1 mega hertz divided by 6 that turns out to be 167 kilo hertz. And we can see that in this plot here this is 14 dB and the intersection of these two asymptotes this one and this one should be the corner frequency. So, let us see this is 1-kilo hertz, 10-kilo hertz, 100-kilo hertz, that is 200-kilo hertz. So, these asymptotes will intersect somewhere between these two and we see that that is indeed happening.

When R 2 is increased to 10 k, the gain goes up, but f c prime - the corner frequency goes down. And now we are in a position to understand why this happens we have this R 2 here in the denominator, and therefore as R 2 goes up f c prime goes down. And that of course, reflects in this graph here. The gain has gone up and the 3 dB point or the corner frequency has moved from there to there and so on; as we keep increasing R 2 the gain goes on increasing, but f c prime the corner frequency goes on decreasing, so that explains our earlier observation. And the important message to take home from here is that there is a tradeoff between gain and bandwidth; we cannot have high gain as well as high corner frequency at the same time.

To summarize, we have looked at amplitude control in sinusoidal oscillators using a gain limiting network; we then looked at the frequency response of an inverting amplifier and explain why the gain drops at high frequencies. In the next class, we will start our discussion of digital circuits, until then goodbye.