**Basic Electronics**
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**Lecture - 32**
**Introduction to op-amps**

Welcome back to Basic Electronics. We now come to a very important and commonly used building block in electronics that is an operational amplifier or op-amp in short. We will start with an introduction to op-amps, and look at their advantages. We will then take a brief look at the internal circuit of one of the early op-amps, namely the 741. We will see the input output relationship of an op-amp and identify the linear and saturation regions of operation. We will look at two approximations that we can make to analyze op-amp circuits when the op-amp is operating in the linear region. Let us get started.

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We now talk about op-amps and we will consider several circuits, which use op-amps. Op-amp means operational amplifier; and it is a versatile building block that can be used for realizing several electronic circuits. And really you cannot think of electronics without op-amps these days it is extremely commonly used and very very useful. The characteristics of an op-amp are nearly ideal, and we will take a look at what these are. And therefore, op-amp circuits can be expected to perform as per theoretical design in most cases that is an advantage, because we do not need to usually worry about the second order effects. Amplifiers built with op-amps work with dc input voltages as well.

Now, if you recall the common emitter amplifier, for example, had coupling capacitor to connect the input voltage to the amplifier. And if you apply an input voltage and input dc voltage that coupling capacitor would obviously, block the DC input voltage and it will not reach the amplifier that is not the case with op-amp circuits. And amplifiers built with op-amps can also work with DC input voltages. And this makes them very useful in sensor applications. For example, you want to measure a temperature or a pressure, so there is a voltage which is proportional to the temperature. For example, that you want to measure and that could well be DC quantity or a very, very slowly varying quantity because temperatures do not normally vary very rapidly.

So, this feature of op-amps is surely very useful. The user can generally carry out circuit design without thorough knowledge of the intricate details of an op-amp.

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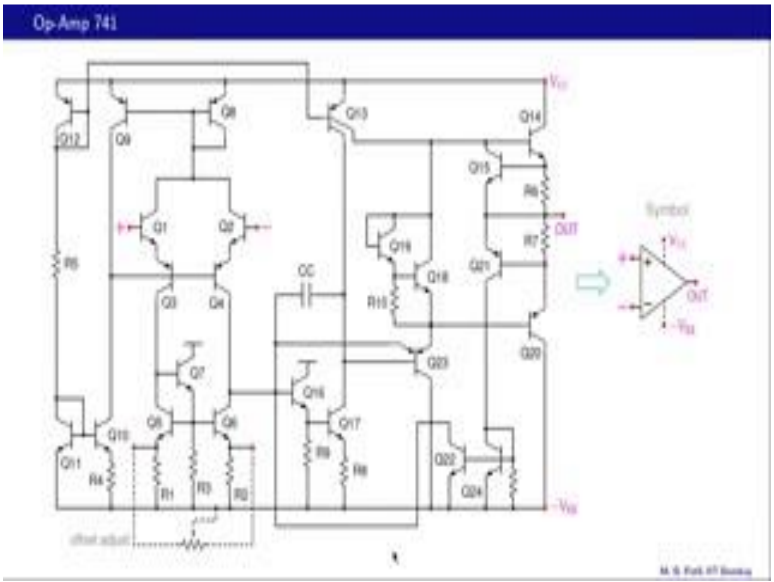


So, generally we do not need to worry about what is inside an op-amp, and that makes the design process simple. And we will see several examples of that. Here is the internal circuit of the 741 op-amp, which is very commonly used, and it is also low cost. And in our likelihood you will probably use these 741 op-amps in your electronics lab courses. What is the first impression of this circuit that it is very, very complex it is, but it is possible to analyze it stage-by-stage. So, there is a first stage here there is a current source which supplies the first stage then there is the second stage and then there is an output stage etcetera. And this analysis can be found in few text books a very nice systematic analysis of the 741 op-amp is indeed possible.

For our purpose, we will not get into how each of these transistors works, what is its purpose and so on, but we will look at this entire op-amp as a blank box and that is the nice thing about op-amp circuits. We usually do not need to worry about what goes inside. Let us look at the pins of this i C now. There are two inputs marked plus and minus here. This input is called the non-inverting input and that is called the inverting input that is the symbol of an op-amp. So, the non-inverting and inverting inputs are shown here. The output of the op-amp is taken here and that is shown here. So, it is an amplifier you apply a voltage between these two inputs and the difference between these voltages gets amplified and that appears at the output.

In addition, we have this power supply nodes V CC and minus V EE. V CC could be 10 volts and minus V EE could be minus 10 volts for example. So, they are complimentary, and this V EE is normally treated as a positive number, so minus V EE is negative. And those power supply inputs are also shown here in this symbol as well. Note that there is no separate ground pin for this circuit; and we will comment on that in the next slide. In addition to these pins that we have already discussed, there are two more pins - these two, and they are mainly for something called offset adjust and we will look at this a little later.

So, all together we have 1, 2, 3, 4, 5, 6, 7; seven pins for the op-amp 741. Now the 741 comes as an eight pin package. So, the remaining pin the eighth pin is not connected. One important point we should observe in this figure is the following. The inputs the non-inverting input as well as the inverting inputs are basically base terminals of transistors Q 1 and Q 2. And therefore, the input current that we see either that current or that current is a base current of BJT. And since base currents are small, they are smaller than the collector currents, but a factor of beta. We often say that these input currents for an op-amp are negligibly small. And in other words we can say that there is a large input resistance between the inputs input terminals of the op-amp.

So, this is the very important point to note and when we analyze circuits we will surely make use of this observation.

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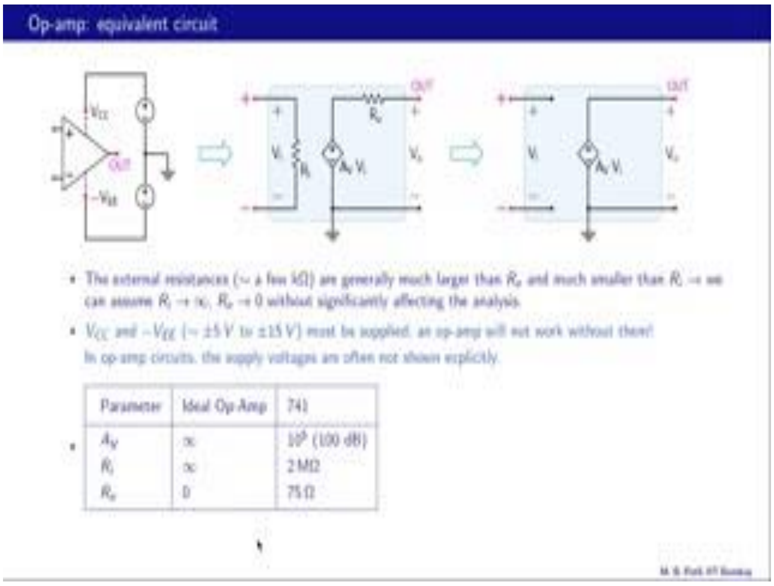


Let us now look at the power supply connections to the op-amp. Let us say for example, this is 10 volts this is also 10 volts; the negative term of this supply and the positive terminal of this supply are connected together and that source has the common ground. If we recall there is no ground pin as such in the op-amp; and if we say that the output voltage is say 2.5 volts what we mean is it is 2.5 with respect to this common ground and that is the same as this ground or this ground shown in these circuits. In our example, both of these are 10 volts. So, this node V CC is at plus 10 volts with respect to ground, and this node minus V EE is at minus 10 volts with respect to the same ground, so that is how the power supply connections are made.

Now, let us look at the equivalent circuit of the op-amp, when it is operating in the linear region. And we will look at what we mean by linear region very soon. So, here is the equivalent circuit. And you notice that its simplicity is striking as compared to the internal circuit of the op-amp that we saw in the last slide. All we have is three components this resistance, this voltage control voltage source, and this other resistance this is the input resistance connected between the non-inverting and inverting inputs of the op-amp these two. This is A V times V i if that is V i this is A V times V i where A V is gain of the op-amp so called open loop gain of the op-amp; and R o is the output resistance of the op-amp. And the output voltage is taken between out and ground that is between this node and this common node here.

The equivalent circuit of the op-amp can be further simplified because this input resistance is generally large resistance and this output resistance is a small resistance. So, let us say this is very large ideally infinite, and then we do not have the resistance here; we just turn a open circuit. And let us say this is small ideally zero and then we do not have a resistance here just a short circuit. And this equivalent circuit is often used and it does explain very well the operation of most of the op-amp circuits.

Let us make a few points. First, the external resistances that we want to connect outside the op-amp are of the order of few kilo ohms, and they are generally much larger than R o the output resistance here the op-amp and much smaller than R i the input resistance of the op-amp. And therefore, with respect to these external resistances we can assume that R i is infinity and R o is 0. And we can do that without significantly affecting the analysis and that is what we have shown over here; R i is infinity and R o is 0.

Second point V CC and minus V EE are in the range plus minus 5 volts to plus minus 15 volts. So, for example, if V CC is plus 5, then minus V EE is minus 5. And these connections must be supplied that means, we must connect this V CC pin of the op-amp to this supply here and the minus V EE pin of the op-amp pin to this supply here. And op-amp will not work without them. So, if you go to an electronics lab, hook up an op-amp circuit and forget to make these connections, then you will not see the output voltage that you would expect.

When we draw op-amp circuits the supply voltages are often not shown explicitly that means, we are not going to show these V CC and minus V EE pins of the op-amp in a circuit diagram, and we are also not going to show these voltage supplies. But it is of course, understood that the V CC and minus V EE pins are actually connected to suitable voltage sources.

Here is a table showing the parameter values for the 741 op-amp. The voltage gain, this gain here ideally infinite for the 741 it is 10 is to 5 or 100,000 which is still a large number. And in terms of decibel it is 100 dB. R i the input resistance ideally infinite for the 741 it is 2 mega ohms. And as we commented this is still much larger than typical external resistance values which are in the kilo ohms range. Output resistance R o that one ideally 0 for the 741 it is 75 ohms. And again as we said it is much smaller than the external resistances.

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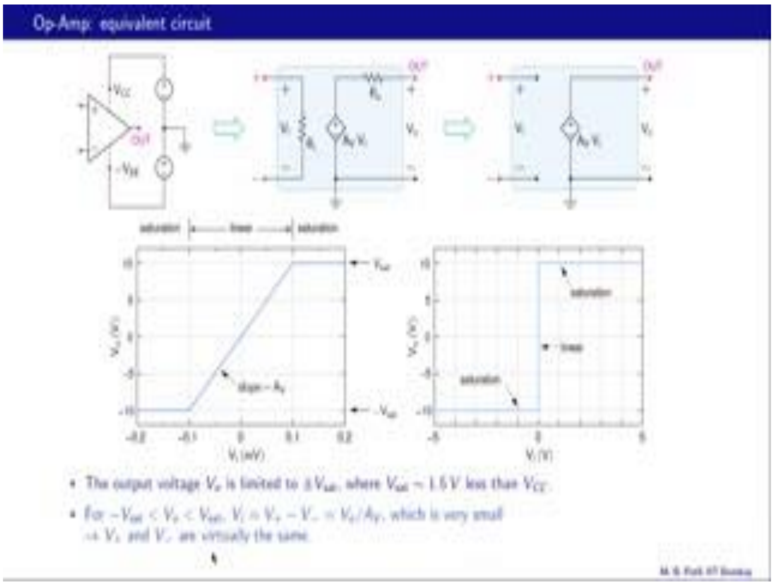


We will now look at the V o versus V i relationship for an op-amp. V o is the output voltage with respect to ground; and V i is V plus minus V minus – this difference here this figure shows the V o versus V i relationship. And as we can see there are two distinct regions one is the linear region, and the rest that and that together we will call as the saturation region. In the linear region, the output voltage varies linearly with the input voltage V plus minus V minus; and the slope is the voltage gain of the op-amp often called the open loop gain of the op-amp. And as we have seen this open loop gains is a large number 100,000 and let us see what the implications of that are.

Now, this relationship is valid only up to a certain point; and at that point, the output voltage saturates either to a positive value or to a negative value. The positive value we will denote by V sat, sat for saturation; and the negative value by minus V sat. Typically V sat is something like 1.5 volts less than V CC for example, if V CC is 15 then V sat would be 13.5 volts. So, then this limit would be plus 13.5 and this limit would b minus 13.5.

In our example, we have taken V sat to be plus 10 volts and minus V sat to be minus 10 volts. Now, this difference therefore is 20 volts and we know the slope of this linear region that is 100,000 or 10 is to 5. And therefore, we can calculate the width of this linear region, what would that be that would be 20 divided by this slope which is 10 is to 5, so that comes to 200 micro volts or the same as 0.2 millivolts, so that means, this entire width is only 0.2 millivolts in this case. So, that is going for minus 0.1 millivolt to plus 0.1 millivolt.

So, notice that these voltages are very small 0.1 millivolt is 0.0001 volt. And these scales definitely are far apart the x and y, these are volts, these are millivolts. And if we plot this V o versus V i relationship using similar scales for the x and y then we will see something like this; so here the input voltage is going from minus 5 to plus 5, the output voltage is going from minus 10 to plus 10. And this entire region now looks like this. So, it has got compressed, you really cannot see the width of this region in this figure.

And that brings us to a very important point for minus V sat less that V o less that V sat that is this range here. V i which is V plus minus V minus is V o divided by A V and because A V is such a large number, V i is very small. And we have already seen that V i is in the range minus 0.1 millivolt to plus 0.1 millivolt. In other words, V plus minus V minus is nearly 0, and therefore V plus and V minus are virtually the same. So, this is a very important observation and we will make use of this when we look at op-amp circuits.

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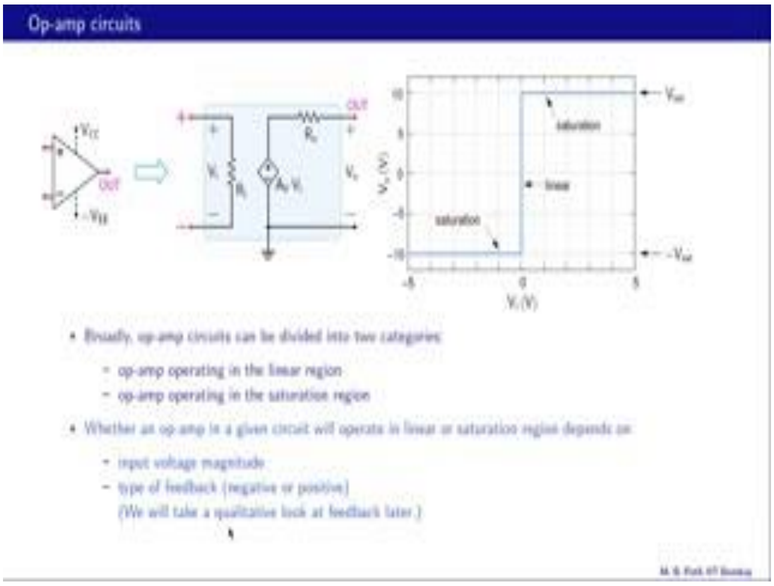


Here is the V o versus V i relationship for an op-amp once again. There is this linear region which is very narrow something like 0.2 millivolts or there about. Then there is the saturation region which covers this part as well as this part. On the positive side, the output voltage saturates at plus V sat; on the negative side, it saturates at minus V sat.

Now broadly op-amp circuits can be divided into two categories; op-amp operates in the linear region - one category; op-amp operating in the saturation region - second category. And in this course, we will have a chance to look at both types of circuits as we proceed. Now, whether an op-amp in a given circuit will operate in linear or saturation region depends on these two factors, one - the input voltage magnitude, and second - the type of feedback. At this stage we do not know what this means exactly, but there are two types of feedbacks negative and positive. And we will take a qualitative look at feedback later.

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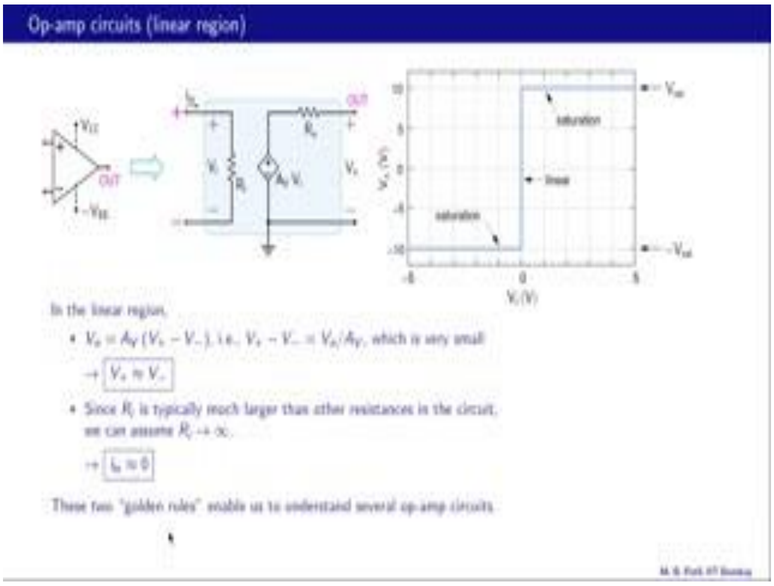


We start with op-amp circuits in the linear region. In the linear region that means, the op-amp is operating somewhere here. What can we say the output voltage is A V times V plus minus V minus that is the input voltage V plus minus V minus; and since A V is very large and V o is limited to this range, this V plus minus V minus which is V o divided by A V is very small. And of course, we have seen that earlier already. And in fact, in this graph it appears like 0. So, in other words, V plus and V minus are nearly the same that is one observation.

Second since R i is typically much larger than other resistances in the circuit; we can treat this as an infinite resistance or an open circuit. And then what it means is that this current is 0, if there is an open circuit here, this current is 0, this current is also 0. So, the input current of the op-amp is approximately 0. So, for all practical purposes, we can ignore it. So, these two are like our golden rules, and they will enable us to understand several op-amp circuits in which the op-amp operate in the linear region. So, let us summarize once again V plus and V minus are nearly the same virtually the same, and the input current of the op-amp is 0.

To conclude we have seen the internal circuit of a typical op-amp and its V o versus V i relationship. We have also seen although an op-amp is a very complex circuit; it is nearly ideal behavior can make circuit analysis easy. In the next few classes, we will look at several op-amp circuits. So, see you next time.