Circuit Analysis for Analog Designers

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Lecture - 62
Circuit injection analysis of distortion in a negative feedback system (contd)

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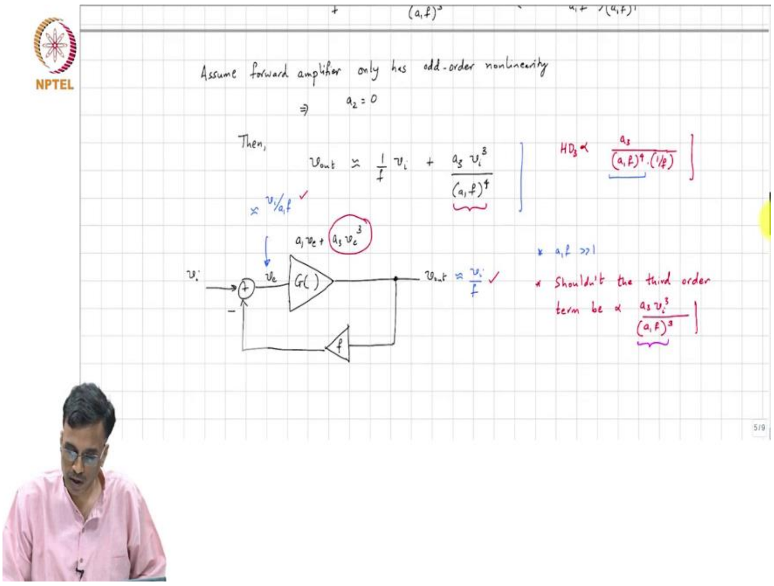

So, I want to consider a special case, and assume the forward amplifier only has odd-order nonlinearity, right? That basically means that a 2 is 0. Then, what comment can we make? v out is approximately 1 over f v i plus a 3 v i cube by a 1 f whole power 4?

$$v_{out} \approx \frac{1}{f} v_i + \frac{a_3 v_i^3}{(a_1 f)^4}$$

Now, what comment can we make about. So, can we get any, I mean why does this result make sense? In other words, remember what is the third harmonic distortion HD 3 is proportional to? The third order the coefficient of the third order term to the coefficient of the first order term.

Ha? Is proportional to amplitude square. Right, but what is that constant which multiplies the amplitude square? 3 a 3 by a 1, right.

And, what is the 3 a 3 here in this case? It is nothing but, a 3 by a 1 f whole power 4 divide by 1 by f, right, ok.

$$HD_3 \propto \frac{a_3}{(a_1 f)^4 \left(\frac{1}{f}\right)}$$

So, the question I would like to ask or understand is. So, if this is telling us that if I double the amplitude, I mean sorry, if I double a 1 keeping, I mean let us say one over f is not changed, because I want the same closed loop gain.

If I double the loop gain, correct? So, if I double a 1, this thing goes down by a factor of 16. HD 3 goes down by a factor of 16. So, why does that make intuitive sense? What happens when?

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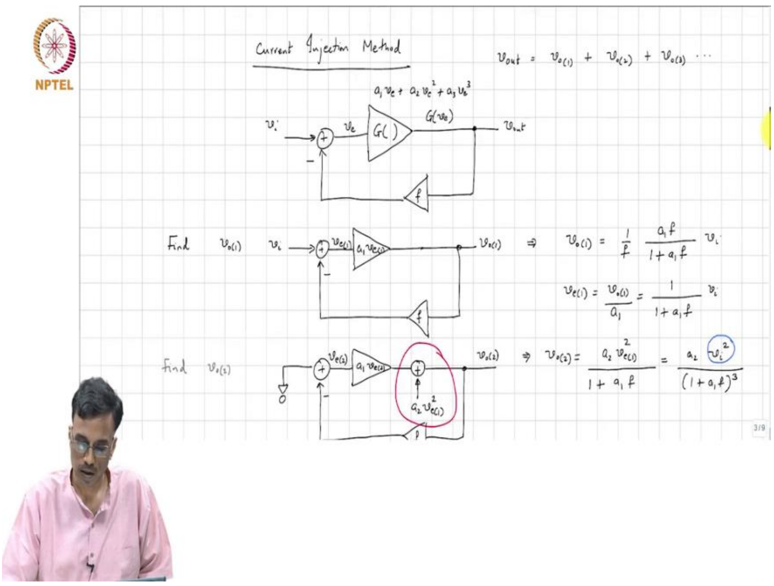

So, let us draw our amplifier again. I will copy and paste it, right. So, what this analysis is telling us is that, if a 1 double, correct. The harmonic distortion is going down by a factor of 16, for the same you know a 3 and the same 1 over f. So, intuitively why do you think, first of all why should the distortion reduce, if a 1 increase?

Increases. So what? I understand. But, yeah why will it suppress non-idealities?

So, basically when you increase a 1, right, where let us say I mean think about this way, the error voltage here is approximately the output voltage divided by a 1.

Correct. So, if I double the, so this voltage. See if a 1 f is very large, the output voltage is approximately v i by f, correct. If the output voltage is v i by f, what comment can you make about the error voltage? Either you can I mean v 1 v i by a 1 f.

Correct, alright. Now if I, double a 1 what will happen to the error voltage? It will become half.

Student: And the output it will be like, that a 3 term will depend on the q. So, it will become.

Ha. Ha.

Student: And here also a 1, like overall output dependence on the third order v i q will be reduced by a times.

Ha I mean. So, simple minded analysis will. So, here is my within quotes, false argument, right. The argument is very subtle, which is why I wanted to discuss this. So, and it is got nothing to do with current injection. Well, if you go and do the an exhaustive analysis and set the limit for a 1 f being large, you will get the same result. Current injection is simply a simpler way of getting at the same result, right.

But, what I am going to discuss now is basically what I would call a side thing, but its sufficiently interesting in its own, right, that I thought I will include it here since we are on the topic. So, if I if the loop gain is very large, right, so a 1 f is much much greater than 1. So, the output, is approximately v i by f. If the output is v i by f, the error voltage to very good approximation is v i by a 1 f, correct.

So, if the error voltage is v i by a 1 f, the output of the forward amplifier the cubic term, right, must be must go as a 3 or rather the output distortion. Basically, you can think of it as the error voltage is being amplified by the amplifier, correct. So, v i by a 1 f is getting processed by an amplifier with a 1 v e plus a 3 v e cube. So, it seems reasonable, that the output will be basically v i by f, which we knew already the fundamental term. But the third order term, as should be I mean should not the third order term, be proportional to a 3 times v cube, which is?

v i cube by a 1 f, the whole cube, right. I mean there is another f cube probably, right, $\left(\frac{a_3 v_i^3}{(a_1 f)^3}\right)$. Sorry, no v i by a 1 f. Yeah, that is it, ok. And, this is telling us that, if you double a 1 the output distortion should go down only by a should go down by a factor of 8, right; however, our careful analysis shows that it goes down by a factor of, By a factor of 16. So, you have an additional power of loop gain, coming in there, right. In fact, I do not know if you noticed it, but even for the second I mean the same argument for a second order distortion.

Yeah. So, we saw that with second order distortion, well, the error will be the error term will be a 2 v e square and that should go as according to our simple minded analysis, it seems very reasonable that it should go down by a 1 f the whole square. But it actually goes down by a 1 f the whole cube, right. Third order it seems like, I hope I have just convinced you that it should go down as a 1 f the whole cube.

But the actual analysis is showing us that it is going down as a 1 f whole power 4, right. And it turns out that, the argument is subtle.

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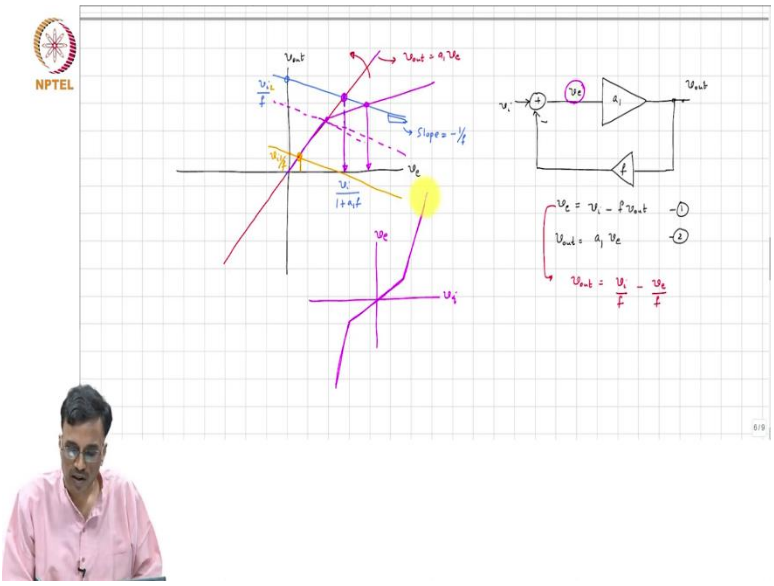

And I would like to before I show you that argument, I would like to explain this graphically. So, let us assume we have a negative feedback system, this is linear. So, this is v e, this is v o, v out I would say, right. So, if we wanted to find the output as a function of the input. So, we would basically say v e is v i minus f times v out and v out is nothing but a 1 times v e.

$$v_e = v_i - f\ v_{out}$$

$$v_{out} = a_1 v_e$$

So, if we want to do this, I mean we are eventually going to move to a situation where the amplifier is non-linear right. So, which is why, we want to use a graph to solve it. So, what will we do if we want to solve this using, solve this graphically? We will plot, v out on the y axis and what you call v e on the x axis, right? And we will. So, we would plot equation 1 and equation 2 on this graph and where the two of them intersect will tell us you know what the output is and what the. So, v out is a 1 times v e. So, that is nothing but, a straight line with a slope a 1, correct. So, this is v out is a 1 times v a.

What is the this equation? How does it how do you plot that? You can see that this can be rewritten as v out equal to v i by f minus v e by f, correct.

$$v_{out} = \frac{v_i}{f} - \frac{v_e}{f}$$

So, that basically means is a straight line with a slope of minus 1 by f, right, alright. And the what do you call, the intercept on the y axis must be? v i by f, correct. And, which is the solution?

Yeah, this point is the, point of intersection that is the solution. And if you, do this, you know this you can just use simple geometry to basically figure out that this is going to be v i by 1 plus a 1 f. does it make sense. So, as a 1 keeps increasing, if this slope keeps increasing, what comment can you make about the point of intersection?

It will move towards which point on the y axis? It will move towards the v i by f Point on the x axis, ok, alright. Now, let us assume that and what happens as you keep changing the input?

Yeah. So, as you keep changing v i by f, what will happen this line the blue line will move parallel to itself.

Right and the point of intersection will basically also move, ok. And likewise, the error voltage will also move, alright. Now, let us say, so if I go on increasing v i from a small value. So, let us say, this is a small v i, right, the point of intersection is here, right and this is that error voltage corresponding to a small v i, right. So, v i 2, say this is v i 1 by f and that is the output, correct.

So, if of course, they are both of them are straight lines, I mean if everything is a straight line, then if I keep increasing v i linearly, the error voltage will increase linearly and the output will also increase linearly. Now, let us say the characteristic of the amplifier is non-linear, right. So, instead of doing this, right, like most saturating amplifiers let us say there is some compression.

So, I will use a different color here, right. So, this is you know in reality of course, the compression will be a lot smoother. But this is good enough to illustrate the point. So, as you keep increasing v i and you plot the error voltage, what comment can you make about the error voltage? So, up to here, you know this is the critical v i, at that break point.

Right. So, if I plot v error, versus v i, right until you reach that critical error, what comment can you make about the point of intersection it will go linearly.

Right. So, beyond if the input increases beyond the critical magenta line there. So, in in other words if the input increases beyond that point, what comment can you make about the point of intersection?

See carefully. Now, hold on. So, this is the red line shows the output. The characteristic of the amplifier without any non-linearity, right, without any saturation. Now, the magenta line shows the output with saturation, correct. So, what this, so what is the error voltage without saturation?

That is this corresponds to this point. What is the error voltage with saturation? Ha. So, with saturation you can see that the error voltage is much higher.

So, if I plot the error voltage as a function of input, what will you get? Ha, correct, right? So, why is this why is this happening? Well, the negative feedback loop is desperately trying to make the error voltage 0, correct. So, well if the gain is very high you know the a small error voltage is enough to make the output v out times f equal to v i. Now, as you go on progressively increasing the amplitude, of I mean the magnitude of the input, the forward amplifiers output is not as high as it would have been if it was perfectly linear. So, the output is actually reducing with respect to an ideal linear amplifier.

Right. So, the negative feedback loop in an attempt to reduce that v, right or to make v out times f equal to v i the only way it can do it is to overdrive the amplifier.

Right. So, if the amplifier characteristic is compressive, right. The error voltage that is developed at the input of the amplifier becomes expansive, right, because the negative feedback loop is basically trying its best to undo the non-linearity of the amplifier, right. Of course, it can only work if the gain of the loop gain is becoming close to infinity. So, it tries its best. So, so this is basically. So, the, so in other words this error voltage is not merely equal to v out by a 1, right. It also has got a component which is basically predistorted to make to try and; to try and undo the non-linearity of the amplifier.

Because it is trying to make the input and output that v out by v out times f equal to v i, right. So, that gives you an additional factor of loop gain, right, which is why you get an extra factor it is not merely, I mean it is very simple to think I mean very straightforward, I mean its appealing intuitively to think that the error voltage at the input of the forward amplifier must reduce if I increase the loop gain. That is correct, right. But that only gives you a factor of you know loop gain the whole cube, correct. But, because of predistortion of the negative feedback loop, you are actually getting an additional factor of a 1 f,

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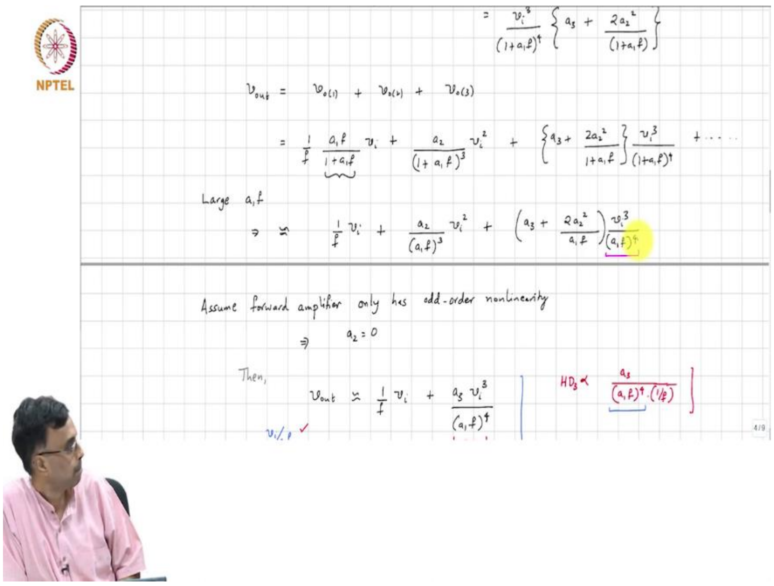

, right which is why whether you look at the third order non-linear term or the second order non-linear term. Remember, that the third order non-linear term is proportional to 1 by a 1 f whole power 4, right. And, likewise the second order term is proportional to a 1 f the whole cube, right. Though you would expect if you simply went by the argument of you know smaller swing, you would basically get only 1 by, 1 by f a square is what you would expect, but you get 1 by f the whole cube, right. So, with that we will stop today. We will continue in the next class.