VLSI Data Conversation Circuits

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Lecture - 15
ADC/DAC Definitions

This is VLSI data conversation circuits lecture 15; in the last class we were looking at you know one of the major non idealities of a quantizer that you are likely to get when you actually implement one. And, that is non uniform step size; a case in point being a characteristic as shown in back here.

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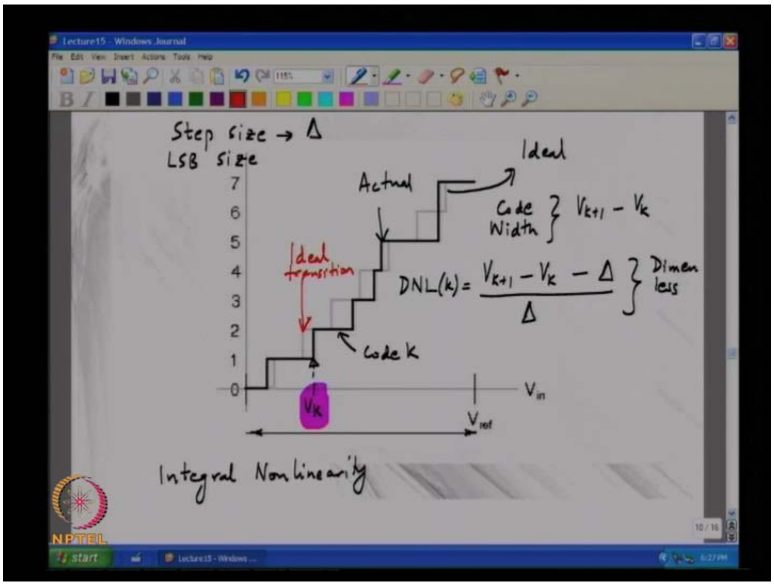

The grey line is the ideal staircase type characteristic that you would like to get. But the black one is the one that you actually get; and we see that the; if we define for a code k if we define V k as the smallest analog input voltage necessary. So, that the output this is code k then the width of the code is nothing but V k plus 1 minus V k; it will dimensions of volts right. And, we know that nominally this must be one step; you know one ideal step. So, instead of talking about the actual code width you might as well talk about the deviation of the actual code width from the; from what is supposed to be you understand? So, if this is ; so that is nothing but V k plus 1 minus V k minus 1 step; and the step size is often denoted by this symbol delta; which is also called the LSB size. So, in which case this becomes V k plus 1 minus V k minus delta; this still has dimensions of volts. So, if you want to talk about a normalize quantity; it makes sense to normalize it to the.

Student: Step size.

To the step size. So, V k plus 1 minus V k minus delta divided by delta is what is called the differential nonlinearity of code k. And, this is being a normalized quantity will be in terms of the you know LSB of the converter. And, these please note this is a dimensionless quantity; is this clear. And, it makes sense to call this differential nonlinearity; because the local size of the step is basically telling you how steep or not so steep; the characteristic is at that in that region is it not; I mean imagine you have a staircase. And, the height of all the steps is the same but in some places the steps are narrow whereas, in some places these steps are wide; I mean clearly you will find it a lot more difficult to climb if the steps are all; very narrow is it not.

And, you will find it easy to climb if these steps are all very wide. So, the width of a step is basically indicating to you how steep the curve is local right; in other words differential nonlinearity is giving you information about the granularity of the characteristic in a certain region right you may also. And, as we discussed the last time around if I specified the DNL for all the codes in the converter; then the characteristic is completely specified right. You can construct the curve from the DNLs; another way of putting this information across where you get also an idea of not just the local variations of the slope. But you get an idea of how globally you are deviating from the ideal staircase ok.

So, is what is called the integral nonlinearity? So, the integral nonlinearity is telling you how far away this transition voltage V k is from the ideal transition; which is the ideal transition corresponding to code k?

Student: ((Refer Time: 05:40)).

So, this is V k this is code k and this is the ideal transition; but V k is the actually transition, right. So, the ideal transition for code k should be at what input voltage?

Student: ((Refer Time: 06:17)).

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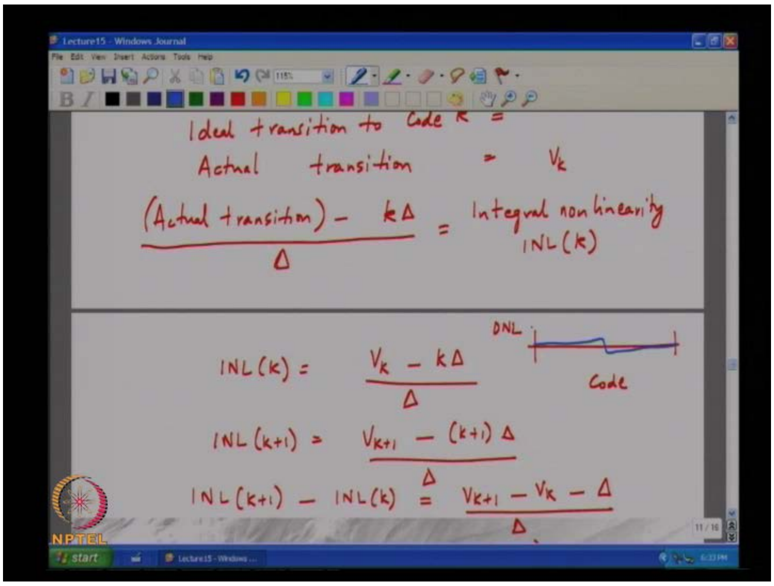

So, if this is code k the ideal transition must be at must be k times delta but the actual one is V k all right. So, the difference minus the ideal transition which is k times delta is a measure of how much the curve; I mean if you kind of imagine this staircase as some curve which is now not really a straight line because this step sizes are all different. This actual transition minus k times delta which is the ideal transition is telling you; how much that curve deviates from the ideal straight line you understand. And, again the dimensions of this are volts and again it does not makes sense to talk about.

Student: Absolute epsilon.

So, you basically normalize this to.

Student: ((Refer Time: 08:06)).

You normalize this to the step size. And, again this gives you this is what is called the integral nonlinearity or INL; and this is also clearly a function of the code. So, INL (k) do you will think differential nonlinearity and integral nonlinearity are independent or.

Student: Dependent.

Pardon.

Student: Dependent; it will be dependent.

So, I mean both are basically giving you information about the code transitions, right. So, they are not independent of one another; they are just different ways of specifying the.

Student: Non ideality.

The same information right. So, this for example, INL (k) is nothing but delta or rather if I talk about everything normalized to delta. Then, this is actual transition which is V k minus k delta divided by delta and INL (k) plus 1 is what V k plus 1 minus.

Student: k plus 1.

k plus 1 delta divided by delta. So, what is INL (k) plus 1 minus INL (k)?

Student: INL of k plus 1.

It is simply.

Student: INL of.

V k plus 1 minus V k minus delta divided by delta and this is nothing but the.

Student: DNL.

D n l of k right; I mean this is an rocket science. You know the INL is giving information about the k-Th transition right. And, the DNL is nothing but the difference between.

Student: k plus.

The k plus I mean the k plus one’th and k transition. So, it makes sense that if you find the successive difference of the INL you can get the DNL and vice versa you understand. I mean these are just even though DNL and INL consist of this are basically giving you the same information; they are just 2 nice ways of giving you an idea of not only the local variations of the characteristic but also.

Student: (( )).

You know the global loop, global picture of the characteristic. For example, if I find that the DNL let me as you a question. So, let us say I plot on the x axis I plot code and on the y axis I plot the DNL. And, I obviously it I will be a I mean a sequence but let us say they are so many codes that when I join all those points; it looks like a curve. So, let us say I get a picture like this; what does this mean?

Student: zero and.

Pardon.

Student: 0 and, if it is symmetric then its depend.

Well, ok. So, let me call this let me draw this in a more legible fashion all right.

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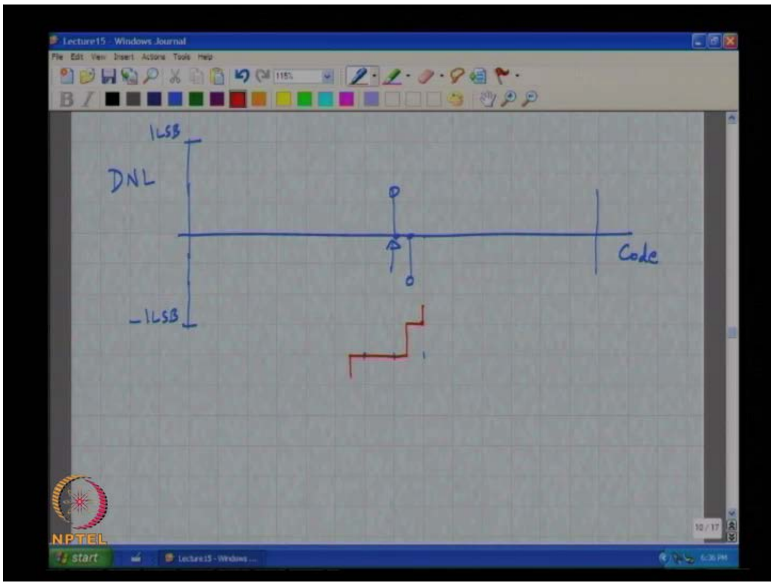

So, let us say I plot; now I have a data converter. And, I plot as a function of code, I plot the DNL normalize to the step size. And, at some point here, at some code I see a big positive jump and here where let us say this is one LSB and this is minus 1 LSB. And, here the in the next code it is like this; what does this indicate in the.

Student: And. So, that INL curve is always possible.

No, no, no what does it say about the can you make any comment on the shape of the.

Student: More deviation it mean.

There is more deviation in the middle but is there can you be a little more specific.

Student: Its DC 4.

No.

Student: No, no I think it is come code is a much along.

So, all that this says is at this code.

Student: Width is increasing;

This code here right has a width which is.

Student: Higher.

Much higher than1 LSB and the next code is got.

Student: 1 LSB.

A code width which is.

Student: Smaller

Much smaller than.

Student: 1 LSB.

1LSB you understand. So, the characteristic locally around mid code is something which looks the first code is much wider than let us say each square here represents the ideal size of the LSB. What this is telling you is that around mid code; the characteristic here is much larger than 1 LSB right and the next step is.

Student: LSB must be smaller.

Much smaller than 1 LSB. So, the code is something like right; the characteristic is something like this you understand. If by chance you see somewhere in the DNL plot you see a minus 1 LSB.

Student: Missing.

You know that.

Student: Missing.

That code is missing what does the DNL becomes more than plus 1 LSB; does it mean that there is a missing code?

Student: No.

Yes.

Student: Yes sir; this is some other value.

One code has got let us say a DNL of 2 LSB.

Student: (( )); no.

Does that mean that there is a missing code.

Student: One code will now sitting across LSB.

Yes. So, what?

Student: It is not a missing code but it may be error flow is limited then by.

No ok.

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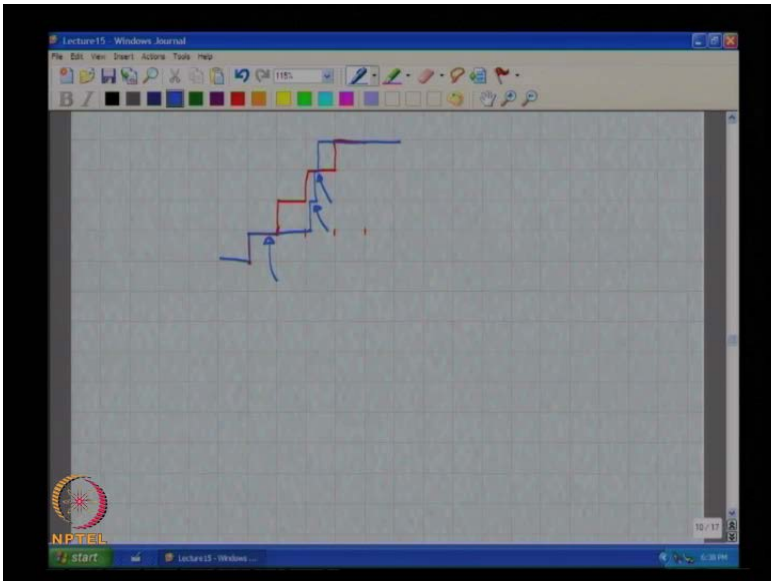

So, let me show you this imaginary scenario the ideal LSB size is like this. So, ideal staircase is supposed to do this correct; and let us say my actual staircase is doing this you understand. So, what does the DNL corresponding to this code?

Student: Plus 1.

Plus 1 right and what is happening to this guy?

Student: It is minus 1.

It is not minus 1 but it is you know.

Student: Close.

Close. Similarly, so is this and so on right because if the if a DNL exceeds you know plus 1 LSB does not mean anything right; you could have it does not necessarily mean that you have a missing cod. Because the widths of many other codes could be so small and contribute to this guy getting really wide; you understand. So, it takes a little while getting used to but you know once you used to this jargon right. And, you know once you do this a few times looking at the DNL plot you will be immediately able to guess; where the where potential problem areas are in the converter you understand. And, please note that and this also very practical reason why you know you specified DNL ok.

The other thing to do if you want to specify the diagram of the characteristic; you will have to specify something which looks like a staircase. And, the deviations should be so small compared to the to the LSB.

So, you will not really be able to make out; imagine if you have to give this information out the information about the characteristic as a graph, as a picture right. The plotting DNL and INL is a very valuable way of doing things. Because otherwise it is not possible to give I cannot think of a reasonable way of putting a across the information; the same information in a more efficient manner; you understand is this clear? So, if you had to draw the characteristic all that will happen will be these transitions will be slightly away from the ideal transitions. And, if you have a large number of bits; then basically your draw you know a staircase which is this big you understand. And, it will be very difficult to discern changes some.

Finally, you only interested in the changes you know what the absolute values the normal values are supposed to be right. And, the DNL and the INL plots are giving you exactly that; the DNL is giving you information about local variations in slope whereas the INL is giving you a broader picture; its giving you equivalently you know a bird's eye view of the entire characteristic. A DNL and INL you know one may ask you know is it important that the DNL is low or is it important that the INL is low or are both important; and when are they important? Well, the answer turns out to be that there are several applications where DNL is very important.

For example, a lot of applications simply cannot tolerate a missing code; sometimes you also have what is called a non monotonic characteristic all right where for example this si also valid stair case.

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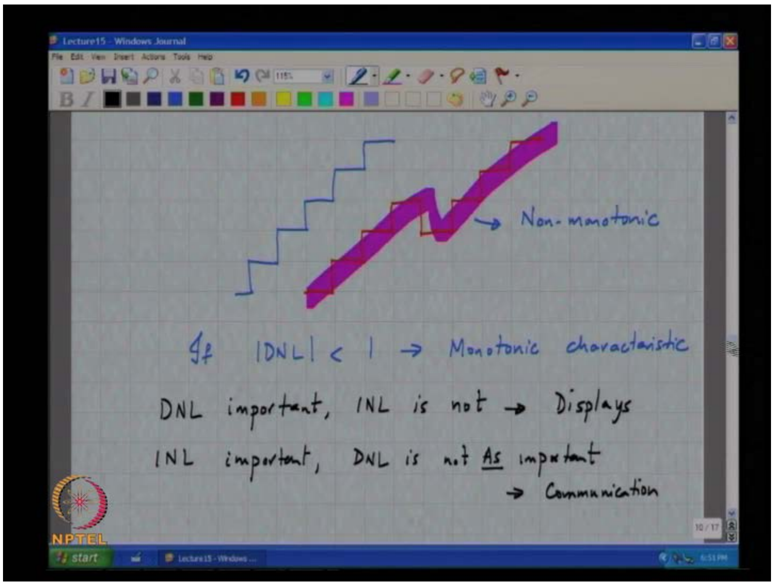

I mean depending on how you implement it ideally you are expecting this but after you implemented it; let us say you got this I mean you might argue that this is not supposed to happen right; yes it is not supposed to. But you know in some convert architectures; if you know bad things happen this is something that can definitely happen right. And, this is what is called a non monotonic characteristic; sometimes there is probably a missing code also. So, in other words the characteristic kind of does that ok.

Student: In this case how do you specify that DNL.

Well, I think I mean see if you will find that the I mean 1 sufficient condition to make sure that the characteristic is non monotonic; I mean is not non monotonic. In other words if it is the characteristic is monotonic is to ensure that the absolute value of the DNL does not exceed; if not DNL is less than 1 then.

Student: ((Refer Time: 22:20)).

All steps exit and all step sizes are between.

Student: 0 to LSB.

0 and.

Student: 1 LSB.

And, 2 LSB right correct; I mean in the limit if DNL is plus 1 then you know a DNL is minus 1 you have. So, if it is the DNL is less than absolute value of the DNL is less than 1 LSB. Then, all steps exist and you will find that this is a definitely a sufficient condition to ensure; that the characteristic is monotonic you understand. And, so where do you think a non monotonic characteristic is a is likely to be a problem? What applications can you think of where can be problematic to have a characteristic which is non monotonic.

Student: No, it is a; there is a feedback loop.

Very good many times when a D C is embedded inside a feedback loop right; you are measuring something you want to change something right depending on what you measure. So, this is a feedback process. And, you know as you all know the loop gain must always be; if you are building a negative feedback system the sign of the loop gain must always be.

Student: Sir negative.

Negative right but now is the curve is non monotonic then what will happen? You will measure something right and let us say what you measure is not what you want and you want that quantity to be increased you will push right. But because of the non monotonicity of the measurement you will find that you are increasing something but the actual output is decreasing.

And, now you know you are totally confused about what to do you understand. And, you will think you are going in the wrong direction and probably change direction. So, whenever ((Refer Time: 25:07)) converters are embedded inside negative feedback loops; it is a big problem to have a non monotonic characteristic; you understand even if. And, again depending on application even if the characteristic is monotonic there are some applications where the DNL is not very important whereas the INL is very important; there are some applications where the exact opposite happens where a DNL is very important but INL is not very important.

The classic examples I had like to give for these situations are DNL is important; while INL is not; example displays all right.

Student: Sir displays a digital to analog converter.

Yeah. So, in a in the same definitions will also hold for a digital to analog converter where you put in the input and the output is analog right. But for example you have picture right and in the olden days before everything was completely digital; there were it turns out that I mean part of the signal chain were you have to convert from analog to digital to be able to take the analog. And, then you know make it interface with the digital T V. For example, right in which case you will have to convert the analog waveform into a digital one and then interface that to a digital display ok.

So, there was a time may be about 10 years ago where this transition was happening displays were all analog. And, then you know then you know then we start getting LCD TV’s and so on. And, then they needed to be some glue electronics to be able to take the analog signal and then generate some digital word corresponding to you know a colour and so on. So, in these imaging applications it is very important to have good DNL; why? Because see in most images right a lot of patches of colour occur in one place; you understand it is not as if very often you have colour transitioning from you know you know black to white it does not happen in 1 pixel you understand.

So, in other words when you scan the beam over definite regions over you know significant regions; the code will only change slightly right. Now, the eye is very good at pick picking up contrast, local contrast. So, if the LSB size is varying right a lot across neighbouring inputs right; where the input is very close that is when the pixel is supposed to be or will also be close is it not; when that when the 2 inputs are very close, 2 analog inputs are very close. But the step size is way different then it will show up as a difference in intensity finally somewhere right. Because you using this digital information to do something else and it turns out that the I is very very good at catching edges and contrasts ok.

So, whereas if this varied slowly from the left side to the right side given that the picture itself is has you know whole bunch of randomness in it; you will not immediately discern that it is not be irritating to the eye; while if you if you put a constant colour pattern like if you put a blue pattern or something you will be easily able to see that the blue here intensity and that is not the.

Student: Same.

Is not the same. But when you know a playing a movie or something like that where the images are changing you will not be able to discern it; whereas, if you suddenly see you know neighbouring pixels where the intensity is very different. Then, you know experienced tells us that it is very easy to catch right. And, applications where INL is important while DNL is not as important is a communication systems; especially wireless systems where you are trying to receive many channels. And, if there is a gentle nonlinearity it turns out that channels which were not supposed to receive right or you not interested in strong channels can actually fold back on to the desired channel.

And, basically cause interference well I will not get into the details. But I just mention it here; what I want to say is that you know whether DNL is important or INL is important these are very application specific thing. But one is for sure you typically you know do not want converters which are non monotonic; of course in a negative feedback loop that be a complete disaster. But even otherwise in general you would not want non monotonic converters ok.

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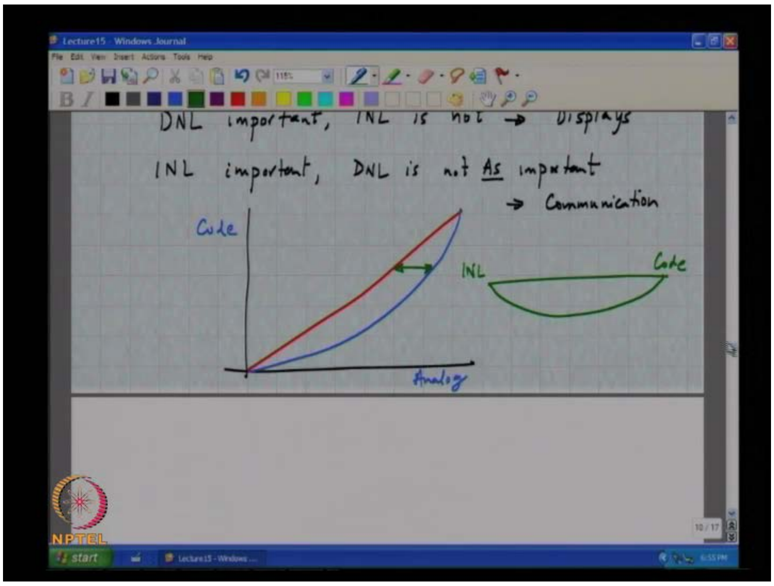

If and as an illustration I will just give you if the ideal characteristic kind of looks like this right; where I am saying that there so many codes that the steps are not visible. And, the actual characteristic is like this all right; the INL will be; what is the INL this is the analog input, this is the digital code right. So, which is the INL here?

Student: (( )).

This is the INL. So, if I plot the INL as a function of k it will be 0 here.

Student: 0 at the end.

And, 0 at the end and.

Student: Peak in the middle; it will peak.

It will peak somewhere in the middle. So, it will be the INL look something like this right; this is code, this is INL you understand.

Student: Sir.

Yes.

Student: For this ground wall current how will we find DNL along the for some codes there may be 2 different leakage.

Yeah. So, the I mean.

Student: Currents for when we.

1 second, yeah. So, often times you will find that when the stuff is non monotonic. Then, different codes will have you know when you are trying to do this transition test; you will find that you will have errors in the test. Because you do not know there are different you know ranges for which you get the same code. So, that will be a pathological condition you will be able to figure that out you know very easily, right. So, usually therefore you know it is often you know you want to make sure that the DNL is always less than when if the DNL is less than 1 LSB; the magnitude of the DNL is less than 1 LSB. Then, you are absolutely sure that the characteristic is monotonic all right.

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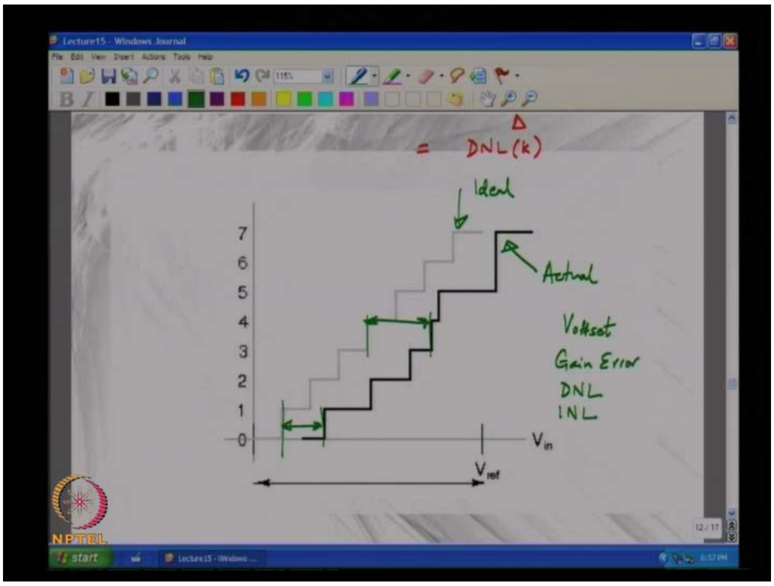

So, going forward in reality of course you will get all these problems together; it is not as if you will have only offset or only gain error or only or only step size mismatch. The ideal characteristic is something like this in the actual one is probably something like this. Now, the question is if you measure an ((Refer Time: 34:42)) converter. And, it has this characteristic; how will you extract it is you want to specify to a customer what the.

Student: ((Refer Time: 34:53)).

We want to tell him what V offset him or her what V offset is what gain error he can expect the DNL and the INL, correct. So, any suggestions on what I should do; clearly this is my ideal staircase one way of doing it is to say this is my ideal transition this is my.

Student: ((Refer Time: 35:23)).

The actual one; so this is my INL right. Similarly, the INL here is this much and so on. So, do you think that makes sense?

Student: ((Refer Time: 35:45)).

You had a good way to do it.

Student: I think maximum, maximum.

I mean. So, let me; so let us say our converter simply had a gain error right; which as we saw is a benign thing. Now, if you simply define the INL as the deviation between the transitions for the ideal case versus the actual case even though this converter is a pretty good.

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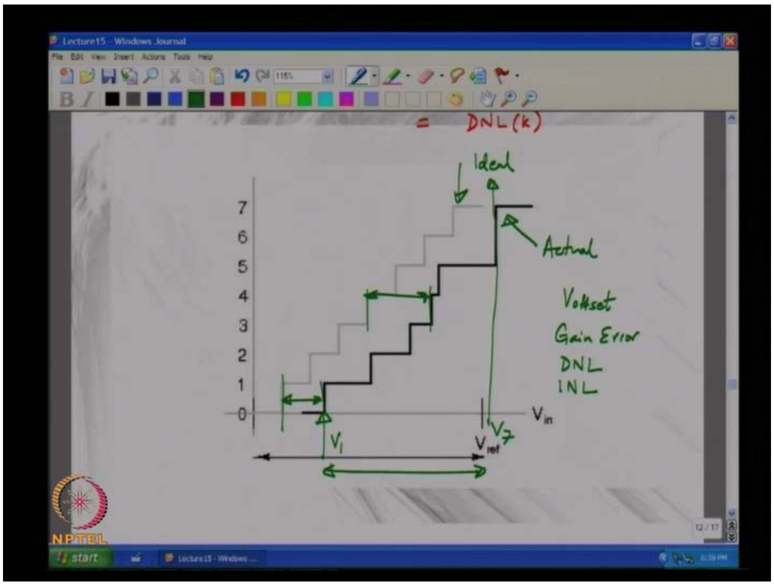

You will see that the INL can become very very large you understand; simply because the slopes are different you understand. And, I mean finally you are trying to sell as many parts as possible by claiming that your part is a very good part. So, you know this is definitely not a good sales idea. So, you should come up with a within codes smarter way of defining things; where all your numbers look good you understand ok. Because you know in many applications anyway the absolute accuracy; you know it is a gain error it does not really matter they will fix it in the system small offset; it does not matter they will fix it in the system right. So, then when what do you think is a better way of defining INL and.

Student: DNL; no instead of using that delta value we can find out the how many value of the widths?

Ok.

Student: That will get rid of to some extent the gain error.

So that is a good suggestion, right. So, what he is saying is that I know that this is my code transition corresponding to in this case 7 right. So, V 7 and this is the code transition corresponding to V 1; I mean all these normalized INL only depend on DNL; for example only depend on the step size correct. So, clearly because of gain error my step size is not the same as the ideal step size that I wanted in the first place, correct. So, the what I would like to do is to try and figure out what my actual step sizes? And, given V 7 and V 1 it is very straightforward to figure out the step size. Because I know I must have 6 steps within this range right I know V 7 and V 1. So, V 7 minus V 1 by 6 is a good is a much better approximation to the LSB; rather than use the ideal LSB I was trying to realise; you understand is that clear you understand?

And, even better way of doing this is to say I will calculate my LSB after removing I mean this is one way of removing the so called gain error. Gain error is nothing but LSB size not being what you wanted to be correct. So, removing gain error means that I will make what I wanted it to be equal to what it actually is; but unfortunately the LSB I mean the step sizes are not uniform. So, you need to come up with some kind of average step size; one way of doing that is to say I will find the last point, the first point I know. So, many codes are there.

So, one way of measuring the average step size is to find the range divide by the number of codes correct all right. And, that will give me my the actual LSB size that I have with my converter. And, I if I use that my INL numbers my for example definitely my DNL numbers all start to look much better than what they I mean what I would have got if I had use the ideal LSB size; does it make sense? And, but this still does not solve the problem of offset; if I had offset and even if my staircase was perfect; the ideal transition point is here, the actual transition point is here. So, if I find the INL it is a constant INL but this is a large number of LSB potentially correct. But otherwise my staircase is actually quite nice; uniform step size gain of one you understand. So, it is not just enough to remove the gain error you must also remove.

Student: Offset.

If you are remove offset; so to find DNL and INL from measurements.

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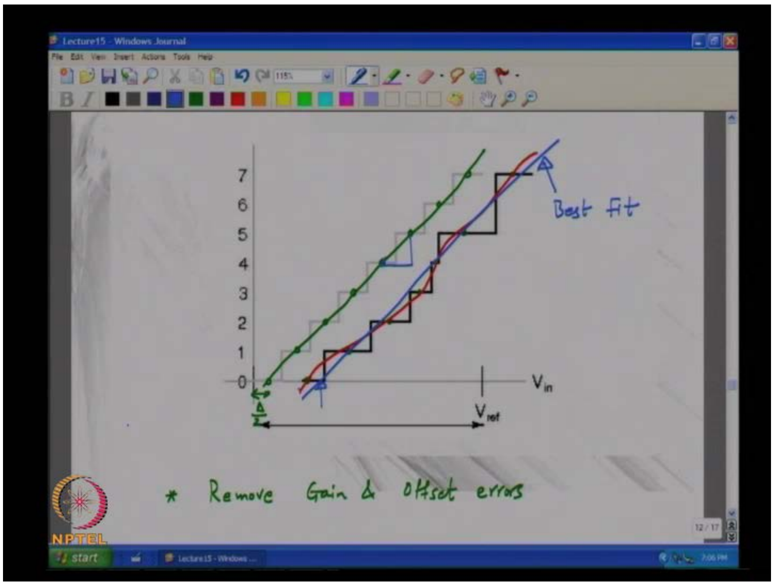

For example, the first step is to remove gain and offset errors. And, how do you remove gain and offset errors? What do you think I mean there are many ways of doing this can you suggest something?

Student: No point they are always ((Refer Time: 41:42)).

Ok.

Student: And, then find out the difference between that and the first transition?

Ok.

Student: That will give you the offset.

Ok.

Student: So, you subtract that offset.

So that is one way of doing it all right; another way of doing it is to say if be staircase was ideal. Then, if I joined all these points when this is a more within codes somewhat more rigorous we have doing things right; the basic idea is a very much the same. You need to get rid of offset error, gain error; if I join the mid points of all these codes what should I get?

Student: A straight line.

I should get a perfect straight line with this offset being equal to delta by 2, correct. Now, I am going to do the same for my actual measured characteristic; I am not going to get a straight line right this. If I join all these points I will probably get something like that. Now, I am going to say let me try and find the best fit straight line which approximates this curve; let us say in the least square sense. So, I will find a best fit straight line which probably does this is clearly not best fit; but let us say this a straight line the one and blue and this is the best fit straight line. So, clearly from the slope of the best fit straight line I will be able to get my.

Student: ((Refer Time: 43:49)).

My true LSB sites correct; ideally if the code if the y goes up by 1 the x must changed by delta right. Now, I have a line whose slope is not quite; what it is supposed to be if this step size is ideal. But once I do the fit; I will be able to extract the slope. And, from that the size of the step that takes care of gain error. And, we know that this straight line must intersect the y axis at.

Student: ((Refer Time: 44:32)).

Step size by 2 right. But it actually is not intersecting it at step size by 2 the difference between the 2 must therefore be the.

Student: Offset.

Offset. So, once you know this you can offset, you can generate within codes the ideal staircase right. I mean you can add offset and gain error to the ideal staircase to get something with a uniform step size. But without gain and offset errors, right.

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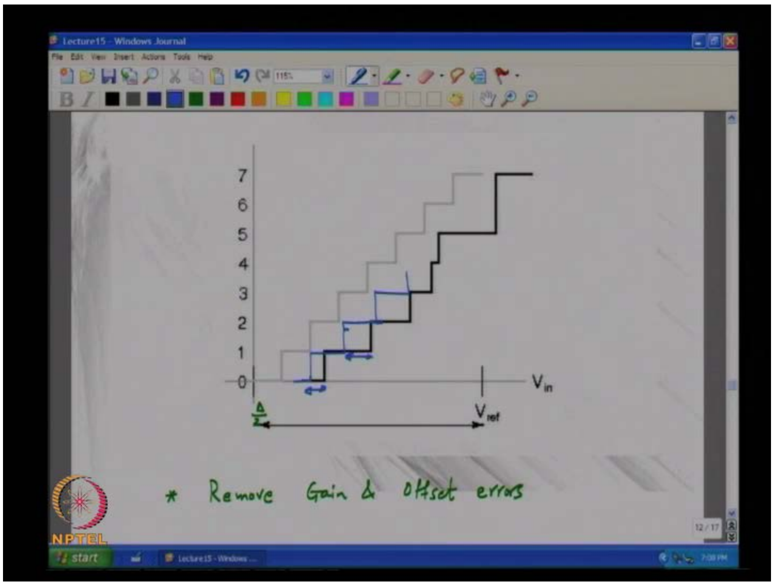

In other words you will probably get a modified something like this; where the step sizes are all the same; the ideal staircase now has an offset and a gain error which is exactly the same as the average gain of; does it make sense at all?

No. So, we know that this slope is not the same as this slope correct; you people understand how I got the other slope? I just fit a straight line that slope is not the same as the ideal slope.

So, if I want I mean the my problem is that this ideal staircase is not a good reference to subtract from; that is the problem. And, that is because I have benign offset and gain error. So, if I add offset to the ideal; if I moved in other words if I moved the ideal over just by the right amount. And, if I change the slope of the ideal staircase by the right amount; then my ideal staircase would probably look like something like this, you understand. So, the deviations from here should give me an INL which is you know a more realistic estimate of what is really happening with the converter; you understand. Because we know that if we simply shift the curve and if you subtract from the ideal characteristic you will get a large.

Student: INL.

INL. But that is not really bad because INL is constant for all codes. Similarly, if the simply a gain error and there was nothing else wrong with the converter; if I had subtracted the actual transitions from the ideal transitions the INL would simply keep increasing as I increase the code. And, again this is not really a it is not a bad converter it is just that there is a gain error. So, what we need to do to get a true idea of the nonlinearity is to remove offset and.

Student: Gain error.

Gain error. And, a one common way of doing it is to find a best fit straight line to the staircase that you actually measure. And, from there go and calculate the true gain and the true offset. And, you can either subtract that from the actual measured values or you add this offset error and gain error to the ideal staircase. And, you subtract the measured ones from the ideal one; which is be in corrupted by offset and gain which is exactly the same as what your converter has. So, in other words the ideal and the actually one will straddle each other; and I am not be so far away you understand. So, fitting is a nice way of simply making sure that; you compare 2 things which are sufficiently close does it make sense ok?

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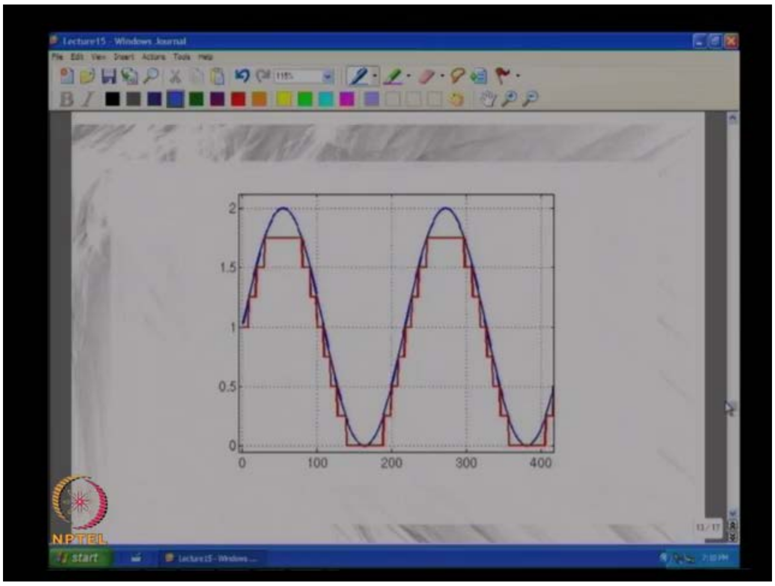

The next thing that we need to so this covers what is called the static part of the quantizer characteristic; we need to figure out what happens when you excite the quantizer with the sinusoid and look as look at its spectrum; I mean clearly quantization involves loss of information. Because main inputs are potentially translate into the same output; which means that you have lost information, correct. So, we will talk about this spectral properties of quantize signals in the next class.