VLSI Data Conversion Circuits

Prof. Shanthi Pavan
Department of Electrical Engineering
Indian Institute of Technology, Madras

Lecture - 24
NTF Design and Tradeoffs

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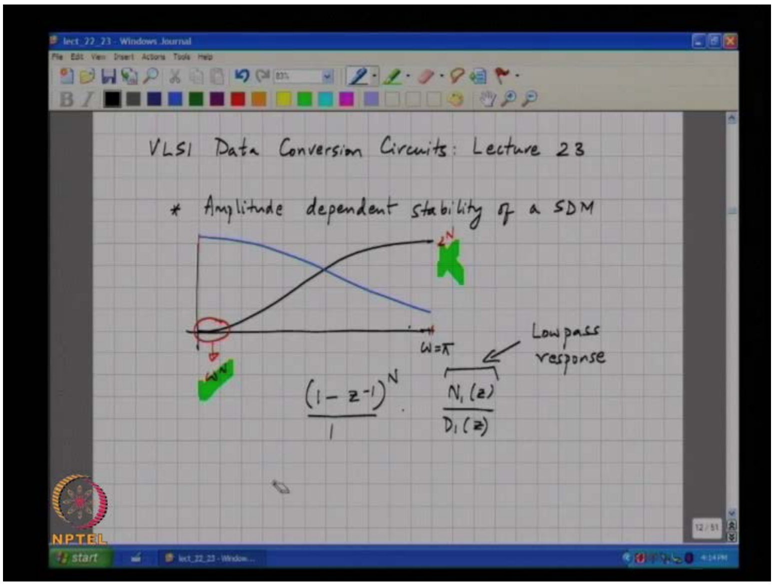

Now, this is VLSI data conversion circuits, lecture 23. In the last class, we saw the intuition behind the amplitude dependant stability of a sigma delta modulator, right. And, the key point was that the input to the quantizer consists of the input to the modulator plus quantization noise which is being.

Student: Shaped.

Shaped by a filter whose transfer function is NTF of z minus 1, right. And, if the gain of the noise transfer function at high frequencies; that is at frequencies around omega equal to pi becomes very large. Then, the variance of the noise riding over the input, which is what is present at the input to the quantizer, becomes very large causing the quantizer to saturate. The quantizer saturates the gain for the quantization noise falls down. If you have a high order loop filter, which is what you will do or you will tend to do in order to push the in band quantization noise low; the closed loop system will become unstable right.

So, in other words the noise transfer function is doing something like this, right. This is problematic, it is too high correct. But this goes as a omega to the power N and this will be 2 to the power n. So, we like this, but we do not like this part, correct. So, the question is, what do we do or can we do anything at all to fix the problem? So, any suggestions? I mean, you want something you do not want something; so, what will you do?

Student: ((Refer Time: 02:39)).

So, the basic idea is to say, if I pass this instead of having; if my NTF is not looking like this, but if I multiplied my NTF with a function of the form which emphasized lower frequencies more than.

Student: Higher frequencies.

Higher frequencies. Then, it seems that I will you know it is like having my cake and eating it too. So, I will be able to have the nice omega to the power N dependence of the in band quantization noise. Well, at the same time attenuating some of the high frequency; high frequency components of the noise. Does it make sense? So, instead of having a noise transfer function of the form 1 minus z inverse to the power N, right; I could for example, multiply this by some N 1 of z divided by D 1 of z, where this is the a low pass response. And, we do not know much about the low pass response other than the fact that we wanted to be high at.

Student: Low frequency.

Low frequency and kind of taper off at high frequencies, all right. So, clearly doing this seems to you know address the problem. However, you must understand that cascading 1 minus z inverse to the N, with another low pass filter; will basically increase the order of the loop filter, right. So, the question is, can we do anything? Can we achieve the same effect without increasing the order of the filter? You understand. So, any suggestions?

Student: 1 minus k z inverse.

Pardon.

Student: 1 minus k z inverse.

Where?

Student: In that loop function.

Oh, well one suggestion is why did not you make this 1 minus k z inverse, but the problem with this is that if k is not 1, what happens to the response of the NTF at DC? What do you want for the NTF to do at DC?

Student: 0.

It must be 0. So, if k is not 1, then the noise shaping is lost, correct. So, that is not a workable idea, all right.

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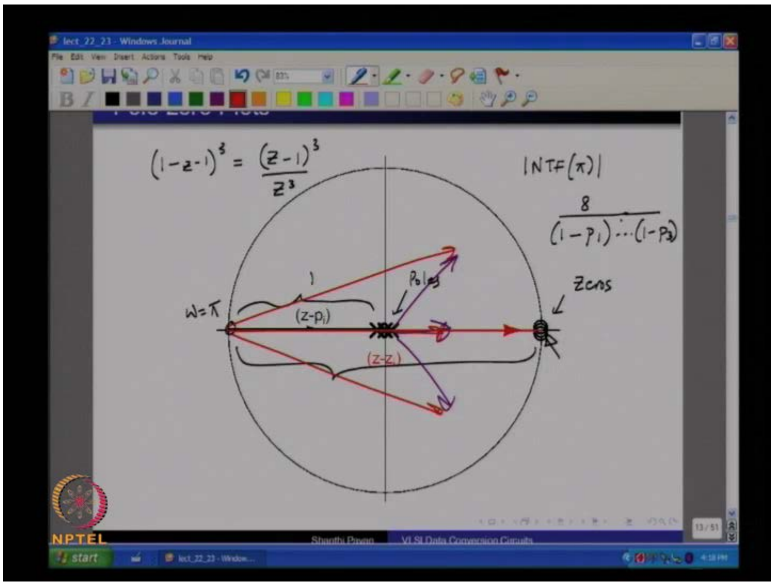

All right, let me again get back to this pole 0 plot. The gain of the noise transfer function at omega equal to pi is at this point, you draw vectors from omega equal to pi which is what I have shown here to the 3 poles. And, where are the 3 poles? In this example, I have chosen 1 minus z inverse the whole cube which is nothing but z minus 1; the whole cube by z cube the 3 poles are at the origin and the three 0s are at z equal to 1. Does it make sense? The question now is, we want to reduce the gain of the noise transfer function at.

Student: Pi.

Omega equal to pi, right. What is it right now?

Student: 8.

It is 8; because it is the, this part is 2, correct. That cube is 8, this happens to be always equal to.

Student: 1.

1. So, the gain at omega equal to pi is 8. We want to be able to not increase the order of the loop filter. So, we still want 3 poles and 3 zeroes and we want to reduce the gain at.

Student: Pi.

At pi, right. There is an additional constraint that you cannot move the zeroes, because if you move the zeroes away from z equal to 1 you will not have.

Student: Noise shaping.

Noise shaping, correct. So, the only I mean, this is a good thing because then you only have to worry about where you are going to place the.

Student: Poles.

Poles. Does it make sense? So, if you want the gain of the noise transfer function to decrease at omega equal to pi, what will you do with the poles?

Student: ((Refer Time: 08:05)).

We know that the gain at pi is basically the location, it is 8 divided by.

Student: Pi minus.

Pi minus, whatever.

Student: P 1.

P 1 into pi minus P 3 correct. So, if you want to reduce the gain at omega equal to pi, it is sorry it is 1 minus P 1; 1 minus p 3. If you want to reduce the gain at omega equal to pi; what should you do?

Student: Try to push.

I mean you cannot change 1. So, you must change.

Student: ((Refer Time: 09:00)).

The locations of p 1, p 2 and p 3. So, where will you put them?

Student: ((Refer Time: 09:06)).

So, if you push these poles in this general direction, right. The low frequency part of the NTF will still be proportional to z minus 1 the whole cube, right. But the gain at omega equal to pi will be?

Student: Proportional.

Now.

Student: Less than 8.

Dependent on the lengths of these vectors which is; obviously, larger than.

Student: 1.

1. So, they will reduce the.

Student: High frequencies.

The gain at high frequencies. Does it make sense? Ok.

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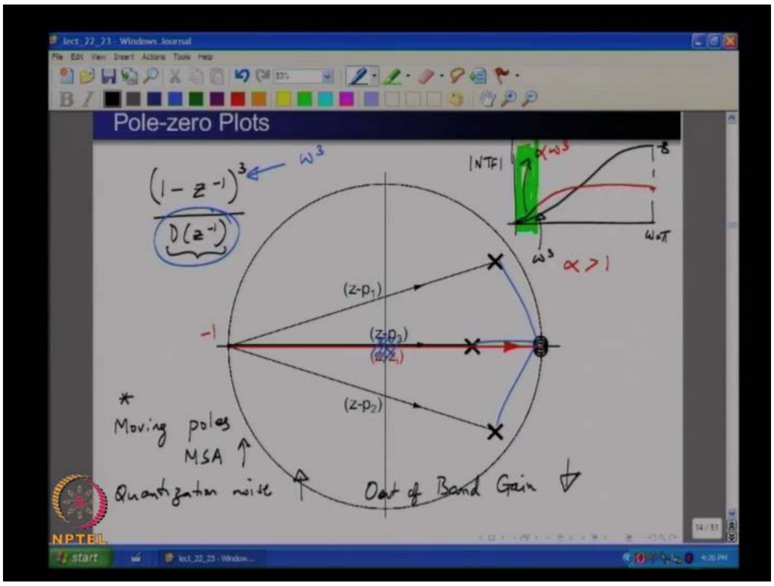

So, for example, if I moved the poles from where they were originally; that is at the origin towards the right. Then, the magnitude of the vectors joining omega equal to pi or z equal to minus 1 to these poles has increased significantly. What was originally 1 seems to have gone to a number closer to close to 2. Obviously, it is smaller than 2, but it is significantly larger than 1, right. So, in other words the noise transfer function is now of the form 1 minus z inverse the whole cube divided by D of z inverse earlier D of z inverse was simply 1, right. Now, D of z inverse is some polynomial in z inverse of order.

Student: 3.

3, right. And, if you choose the poles of the NTF; in other words the roots of D of z inverse properly by I mean, when I say properly it means that in the generally in the towards the right. You know towards the right. Then, the magnitude of the denominator at omega equal to pi is larger than 1. Therefore, reducing the gain of the noise transfer function at high frequencies and this is possible without increasing the overall order of the noise transfer function. Does it make sense? So, what was originally something like this? This is mod NTF. This is omega equal to pi, this is 8, all right. Now, for this pole constellation, what do you think the gain will be at omega equal to pi is smaller than?

Student: 8.

Smaller than 8. So, let us say it is something like this. What can you say about the gain at the origin; at omega equal to 0 or z equal to 1?

Student: 0.

Of course at z equal to 1, it is 0, right. For small omega how does this go? The original NTF 1 minus z inverse whole to the 3.

Student: ((Refer Time: 12:55)).

It mod NTF.

Student: Omega power cube.

Omega cube. Now, how does it go?

Student: ((Refer Time: 13:12)).

It will be, it will go as constant times.

Student: Omega.

So, at the origin this guy will have gone as omega cube. Now, because of the poles being pushed close to the zeroes; what do you think will happen to the gain at low frequencies? It will still go as omega cube; because you have 3 zeroes at z equal to 1. But will it go faster? I mean will it go as 1 times omega cube or will it go as 5 times omega cube or will it go as 0.1 times omega cube? Look at the picture that is the key to, ok.

Student: Smaller.

No. No, it is not smaller; it got to be larger, right.

Student: ((Refer Time: 14:19)).

Now, it has come inside. So, the distance is less than.

Correct, so?

Denominator is less than 1, larger than ((Refer Time: 14:24)).

Great, that is absolutely, right. So, earlier the poles were sitting here at the origin, right. And, at z equal to 1, correct. This in the neighbourhood of z equal to 1, always evaluates to omega cube, right. Now, the only point of contention is what does this do, at?

Student: Small frequencies.

Small frequencies, correct. And, this is clearly; earlier, what was 1? These vectors are now reduced in magnitude which means that.

Student: Denominator is less than 1.

The denominator is less than 1. So, this must go as. The red one must go as k times omega cube; where k or alpha times omega cube. Since, we have been using k all over the place alpha is definitely greater than 1, right. Whereas, the original NTF would have gone as simply omega cube. Does it make sense? All right. So, in English what does this mean? What has happened now? By moving the poles in this fashion, what has happened or what do you hope has happened to the maximum stable amplitude?

Student: ((Refer Time: 16:14)).

M S A has gone. Hopefully up, right. What you, what can you say about the in band quantization noise?

Student: ((Refer Time: 16:35)).

Has gone up or gone down?

Student: Gone down. In band or ((Refer Time: 16:45)).

In band, in band quantization noise.

Student: ((Refer Time: 16:49)).

The in band quantization noise is the, this integral of NTF square in some band here. It is gone up, right. So, quantization noise is gone up. What has happened to the out of band gain?

Student: ((Refer Time: 17:11)).

Has gone.

Student: Down.

Down. So, what I bring like to, bring to your attention is the following. The In band quantization noise has gone up and the out of band quantization has gone, I am sorry the out of band gain has gone low or gone down right, ok.

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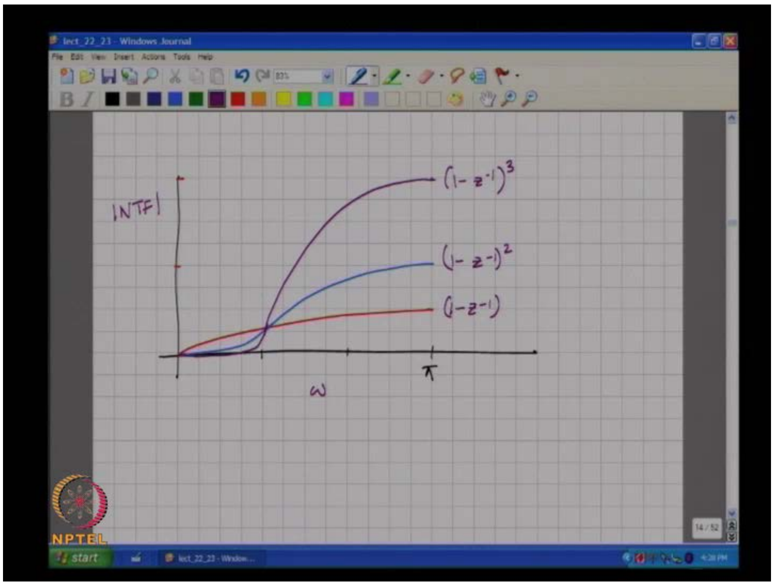

And, this is not just a coincidence. Let us look at the NTF'S; that we have seen at pi all right. So, for the first order in a NTF, how does it look? How does the NTF look at the origin?

Student: Proportional to omega.

It is goes as omega, right. And, what is it at out of band? It is 2; so, it looks like this. For the second order how does it look? Near the origin, it is omega square and at pi.

Student: That is 4.

It is 4, all right. Now, what happens for the third order modulator?

Student: Omega cube of the ((Refer Time: 18:43)).

Omega cube and then this goes as.

Student: 8.

Goes to 8, all right. So, this is mod NTF and this is omega, and this is 1 minus z inverse is 1 minus z inverse the whole square, this is 1 minus z inverse the whole cube. And, what trend do you see?

Student: ((Refer Time: 19:23)).

So, whenever we are doing better in band, we seem to be doing worse out of band, right. And, not only when we change the order, but also when for the same order we move the poles in such a way as to reduce the out of band gain we seem to be doing.

Student: ((Refer Time: 19:53)) in band noises.

The in band noises increases. You understand; it turns out that this is a fundamental property. And, we will come to this in a couple of minutes. So, I am going to skip all these slides; some of these are just completed stuff we have done all this before.

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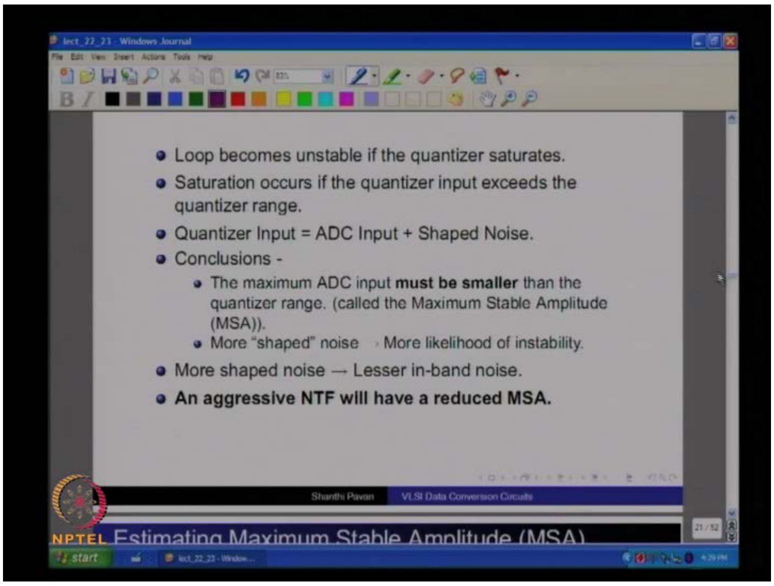

So, again to retreat the maximum ADC input must be smaller than the quantizer range right that this is the; so, called u that we have been talking about. And, which has more shaped noise; then, it means that there is more likelihood of instability. And, as we have just seen now we made a passing observation, that the more the shape noise the smaller seems to be the.

Student: In band noise.

In band noise, right. Now, the evidence is simply circumstantial, right. We have seen 1 minus z inverse, 1 minus z inverse the whole square and 1 minus z inverse the whole cube as well as 1 minus z inverse the whole cube by D of z inverse. And, in all these cases, it seems like if the out of band gain goes up the in band gain goes down, all right. But that does not mean that it is true for everything, but it turns out that it is true for all noise transfer functions that we encounter in practice. I will derive that a little down the line. An aggressive noise transfer function loosely speaking is one which has much smaller in band quantization noise, than a nonaggressive one right. An aggressive one if you have an aggressive noise transfer function in an attempt to push the in band quantization noise lower, it must follow that the out of band gain must be.

Student: Higher.

Higher. If you have a higher out of band gain, what can you say about the maximum stable amplitude?

Student: Less.

It must fall. Because for the same quantizer input range, if you have a higher out of band gain; it means that the variance of the noise riding above the input is higher. So, in order to keep the quantizer happy, you need to reduce the input amplitude; thereby reducing the maximum stable amplitude of the modulator loop, right.

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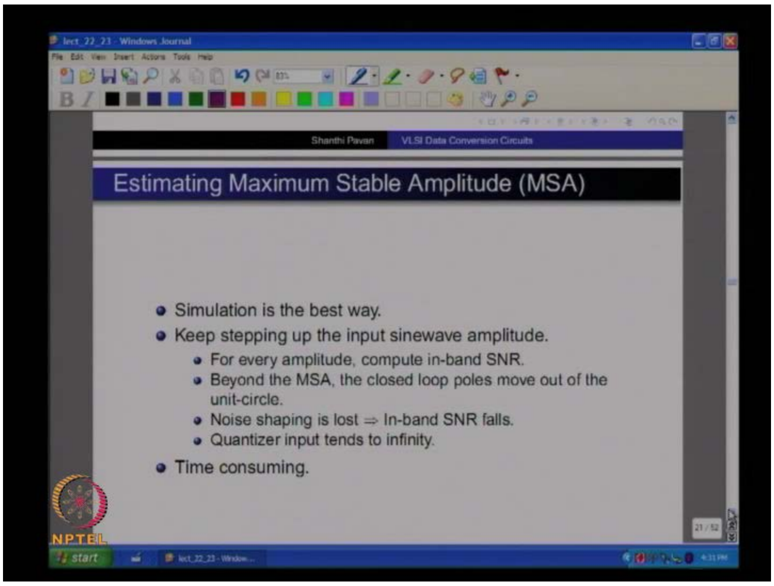

All right. Before, I go further I just like to mention you know how one might estimate the maximum stable amplitude of a modulator in practice. This is obviously, something which is very relevant, right. So, simulation is the most reliable way of doing it, right; in the given that doing this analytically, it can be a very messy effect. So, one thing you could do is put a sinusoid with some amplitude. Look at the state variables inside, if none of them blow up you are fine. The, this amplitude is within the stable range. You go on stepping up the amplitude and right, you can do this; unfortunately this takes a lot of time.

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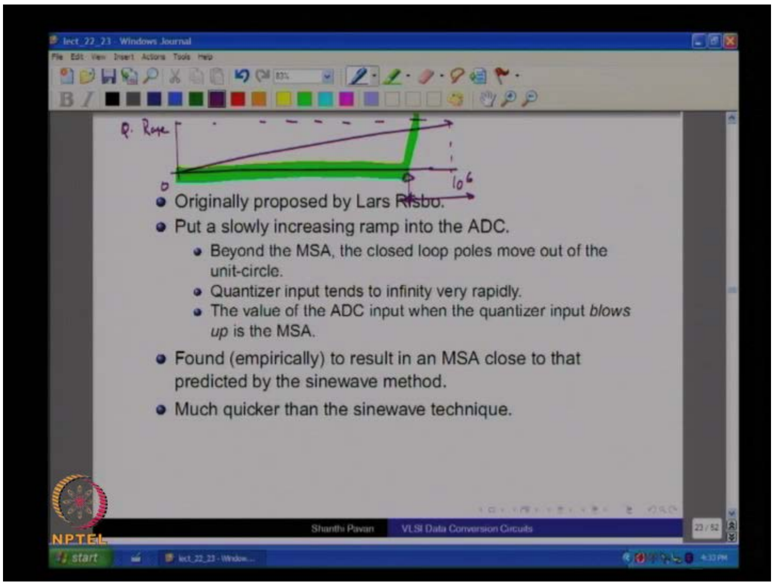

So, another technique is to take a very slowly varying ramp, right. By slowly varying, I mean you know this varies from 0 to full scale of the range of the quantizer, right; over say a million steps correct. So, they are very very slow ramp and monitor the input to the quantizer. We know that when the modulators become unstable, what happens to the input of the quantizer?

Student: It blows up.

It blows up, right. So, rather than plot the input to the quantizer, you can plot the log of the input to the quantizer; in which case what will happen is that it will look nice and clean up to somewhere here, right. And, then once you start exceeding the maximum stable amplitude, the magnitude will blow up which means that the log will also blow up. And, you will see something like this. And, then the ratio of this to 10 power 6; how long you have gone before the input to the quantizer blows up is an estimate of the maximum stable amplitude. And, people have found that, this is a good way of doing things.

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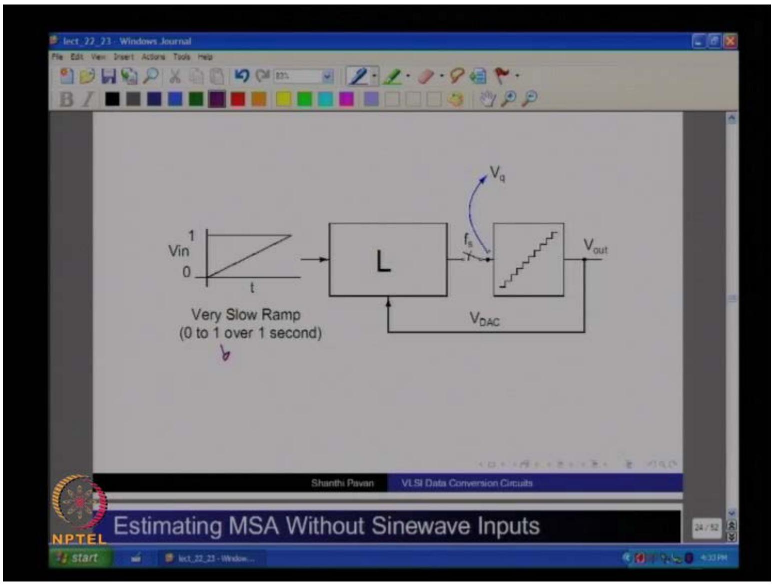

So, this is what I was talking about. It is a very slow ramp where one stands for the quantizer range, right. This is a loop filter and we keep monitoring the input to the quantizer.

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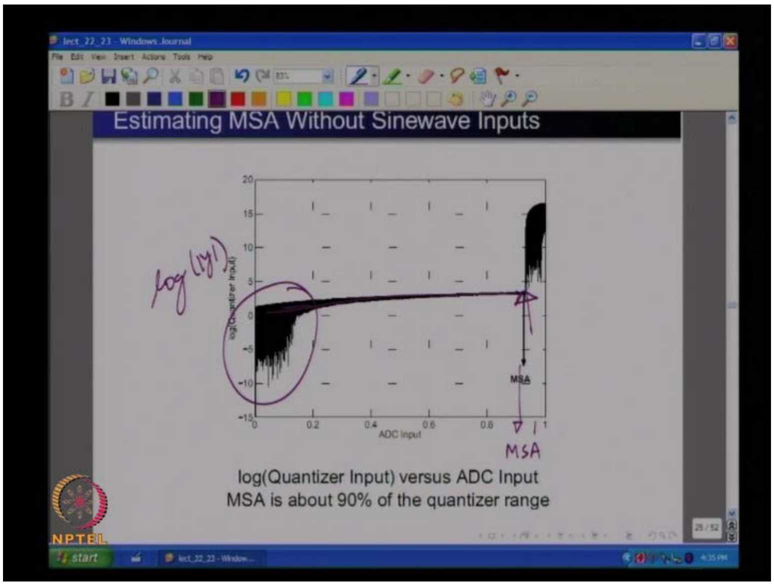

And, you will get a plot like this. So, please note that this is log (mod y). When you start at z, I mean the initial part is because the input is close to 0, right. So, the y will be hovering you know up, above and below 0, right. So, if you, since it is 0; if you take its log, it will be negative, correct. And, then as you keep increasing the input amplitude, you can see that in general, the magnitude of y increases. And, at a certain point in time it can also be mapped to a certain input. You can see that the log of the y just blows up which means that y is a simply gone, infinity. Which means, that this is the maximum stable amplitude. In this particular example, it is about 90 percent of the quantizer range. Is this clear? All right, I will come back to this a little later.

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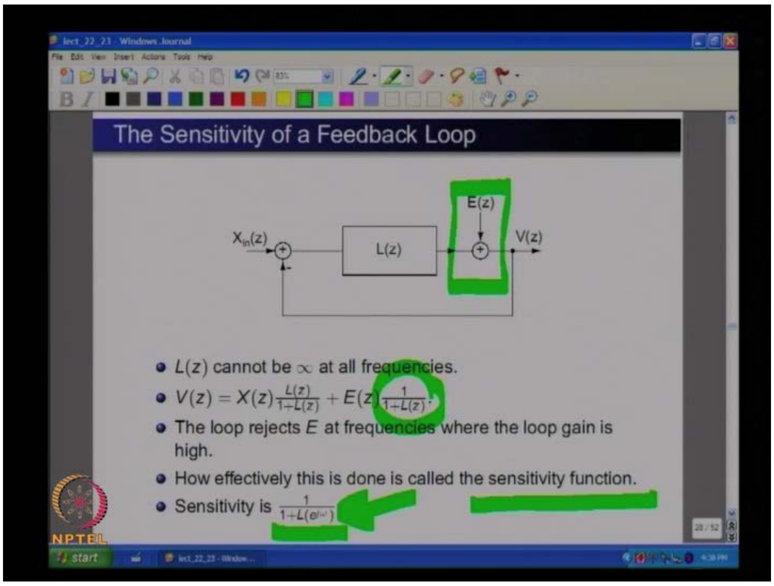

So, now let us digress a little bit and see if we can get any intuition about or rather we can get throw more light on the fact, that the in band performance and the out of band performance of a noise transfer function seem to be related. We seem to be, not be able to do better in band without worsening the performance out of band, right. So, to understand this one needs to kind of rewind a little bit and refresh or familiarize oneself with some terminology and some results. This is an example of a negative feedback loop all right. This has got nothing to do with say a delta sigma modulation, right. This is a standard negative feedback loop. And, if the loop gain is very high, correct; then what is V? At all frequencies where L tends to infinity or L is very large, we find that V must be the same as the input, correct. And, that make sense because V can be written as X times L by 1 plus L plus E times 1 by 1 plus L, right this is all well know stuff.

So, in other words at frequencies where the loop gain is very large, the output is completely devoid of E. In other words, the loop has completely rejected, this error injected at the output of the loop filter or the loop is extremely insensitive to E, not to L to E. At those frequencies where the magnitude of the loop gain is infinite, right. Now, the ratio 1 by 1 plus L (z) evaluated on the unit circle is a measure of how effectively the feedback system rejects disturbances or noise injected at its output, all right. And, classical control, this is being called; what is called the sensitivity function of the loop ok. Please note that this is the function of the loop gain, all right. Now, in a delta sigma modulator assuming the quantization noise is additive; the sensitivity function is the same as the.

Student: NTF.

Noise transfer function, correct. I mean now somebody told you that this is the block diagram, you would immediately say that this represents the additive noise of the quantizer. And, therefore, you can identify the sensitivity function of a negative feedback loop in the delta sigma context by in noise transfer function of the loop, correct.

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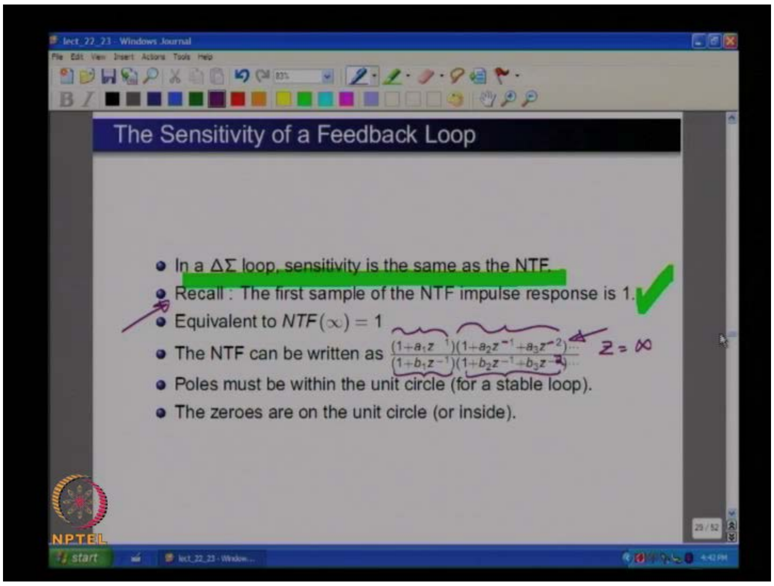

And, it turns out that since in a sigma delta loop the sensitivity is the same as the noise transfer function. Some, very interesting results from control can be applied and to get there, let us recall the first thing which is the first sample of the impulse response of a noise transfer function must be.

Student: 1.

1 and why is this happening?

Student: ((Refer Time: 30:26)).

Because you cannot have a delay free loop, all right. In the frequency domain, this means that the noise transfer function evaluated at z equal to infinity must be.

Student: 1.

Must be 1, correct. Now, if the noise transfer function has poles and zeroes on slash within the unit circle. Of course, the poles you would expect to be well within the unit circle, the zeroes are either on the unit circle or sometimes it so happens, that the zeroes move a little bit inside. For example, when the integrators have finite gain, you can show that the zeroes of the loop, right; instead of being z minus 1 or 1 minus z inverse will be 1 minus alpha z inverse, where alpha is slightly smaller than 1 ok.

So, you can always factor the noise transfer function into something of this form. So, 1 plus a z inverse is the first order factor. If you have complex conjugate poles, you can factor them into 1 plus a 2 z inverse plus z 2; I mean a 3 z to the minus 2 and so on. And, the denominator is 1 plus b z inverse b 2 z inverse plus b 3 z to the minus 2 and so on, right. And, the roots of all these factors, that is the roots of this factor, this factor, this and this will all be; for the poles they will be?

Student: It is unit circle.

Definitely, within the unit circle, if you want to have a working modulator right the zeroes at the most they can be?

Student: On the unit circle.

On the unit circle, all right. And, clearly this form of writing the NTF satisfies this fundamental condition which is at the first sample of the NTF impulse response must be equal to 1. Why? Because if I take this and evaluate it at z equal to infinity, what do I get?

Student: 1.

I get 1, you understand. In other words any noise transfer function can be written in this form. Is this clear?

Student: 6 zeroes can be inside the unit circle or.

Yeah the zeroes can be inside the unit circle.

Student: Not the outside.

I mean most of the, in most practical cases you will find it there either on the unit circle or inside. So, you design them to be on the unit circle; however, you do finite gain effects and so on. They actually might move in a little, is this clear; all right.

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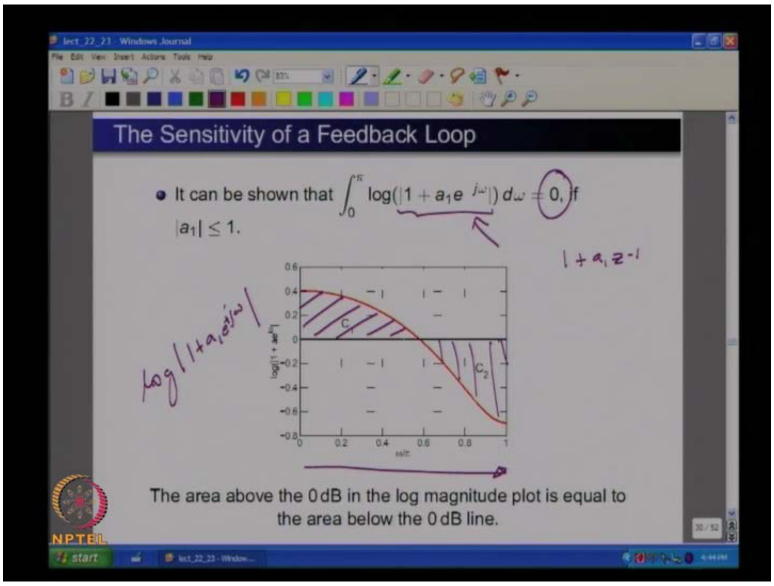

Now, it turns out that it can be shown that if I evaluate the integral from 0 to pi of the log of the magnitude of a term 1 plus a 1 e to the j omega from 0 to pi. Then, this turns out to be equal to 0. You understand? Let me repeat this again. I have a term 1 plus a 1 e to the j omega. In other words this is nothing but 1 plus a 1 z inverse evaluated on the unit circle, right; I find it is magnitude only take the logarithm and integrate it from.

Student: 0 to pi.

0 to pi, all right. And, it turns out that this is 0. It is not too difficult to show, all right. Now, since a picture is worth 100 words, it is nicer to draw a picture. So, if I draw on the x axis omega or omega by pi and on the y axis I draw log of 1 plus a 1 e to the minus j omega e to j omega. Then, the net area is 0. In other words the area of this log magnitude curve above 0 must be the same as the area below 0. Is this clear? I mean, if we multiply

this whole thing by 20, nothing changes, right. And, then you can express everything in dB. So, if you plot the log magnitude of 1 plus a z a 1 z inverse; where a 1 has a magnitude smaller than 1, then the area above the 0 dB line will be exactly equal to the area.

Student: Below.

Below the 0 dB line.

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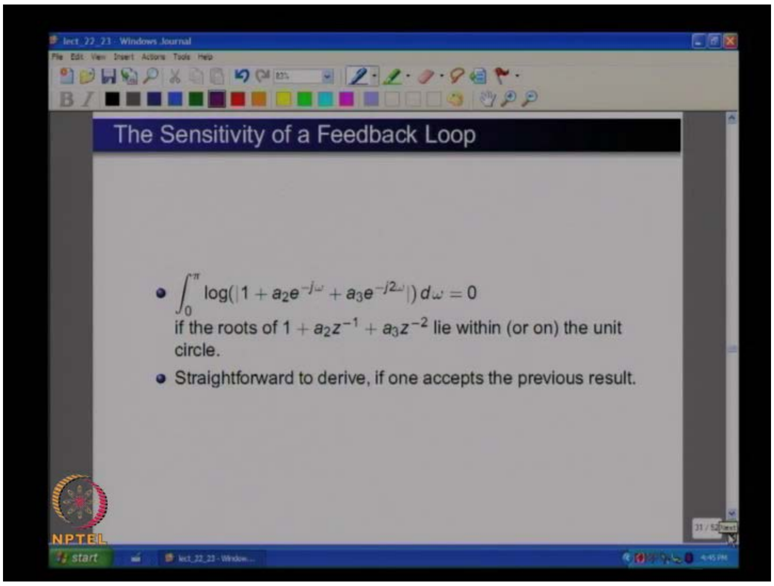

So, now consider the second order factors. If the poles lie within the unit circle, you can always break this up into a product of.

Student: 2 first order terms.

Two first order terms; where the coefficients are now complex conjugate, right. If the roots are complex, otherwise there are 2 real poles. And, if the, if you accept the previous result; then, you can show that if you plot the log magnitude of this transfer function. Then, again the area above 0 must be equal to the area below 0 or in dB the area above the 0 dB line must be the same as the area below the 0 dB line, correct.

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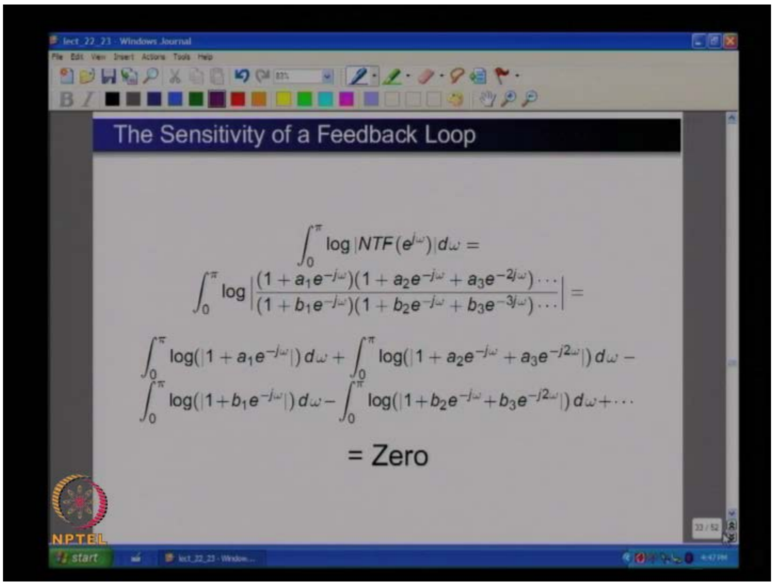

Now, that we have accepted this, our NTF is simply a log of.

Student: ((Refer time: 37:31)).

I mean whatever, log magnitude of the NTF is simply nothing but log magnitude of products of terms like this, correct. And, each one of them individually evaluates to.

Student: 0.

0, right. So, in other words the log magnitude of the noise transfer function integrated from 0 to pi must therefore be.

Student: 0.

0, is this clear? So, in other words if you plot the log magnitude of the noise transfer function and the NTF is stable. And, the zeroes of the NTF are either on the unit circle or inside; then, the area of the log magnitude of the NTF above 0, must be equal to the area.

Student: Below 0.

Below 0, right. I mean this fits in well with all our circumstantial evidence namely, right. You know when we attempted to increase the out of band gain, correct; what would we find the in band noise was getting better. On the other hand, when we reduce the out of band gain which is equivalent to saying; if you reduce the out of band gain, the out of band log of the gain also reduces. Which means that, that area above the 0 dB line is reducing; which means, that the area below the 0 dB line must increase. And, where is the magnitude, where a log magnitude less than 0? For the NTF, at what frequencies is the log magnitude smaller than 0?

Student: In band frequencies.

Pardon.

Student: In band frequencies.

At in band frequencies, correct. So, right

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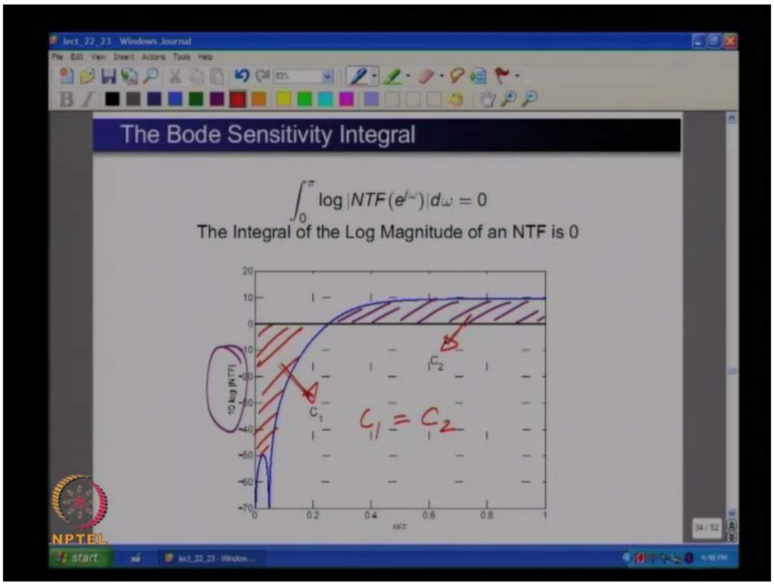

So, this area. So, if you plot say log NTF; the area of this above 0, must be the same as area below 0, right c 1 which is this area and c 2 which is this area must be the same.

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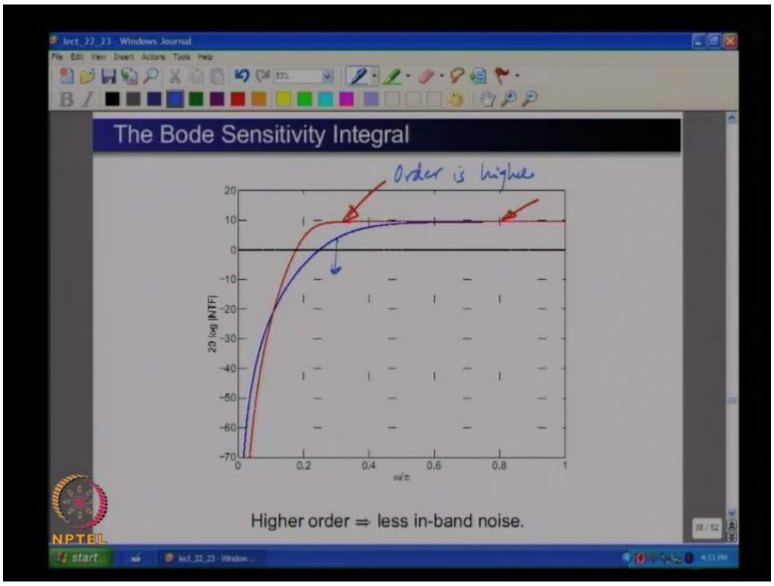

And, this is what is called the Bode Sensitivity integral, all right. And, therefore, in English this means that good in band performance can only be obtained at the expense of.

Student: Poor out of band.

Poor out of band performance; which is something we have seen all along, right. For example, a 1 minus z inverse has good out of band performance because out of band gain is only 2, but it is in band performance is not great. A second order modulator has a poorer out of band performance, but better.

Student: In band.

In band performance and so on and so on, all right. So, let us skip this for the time being. So, this also I mean please note that we have not said anything about the order of the loop filter so far. This is irrespective of the number of poles and zeroes in the noise transfer function. So, if we had 2 noise transfer functions with the same out of band performance right. But if one had a higher order than the other, then you can do better in band and the reason is that.

Student: ((Refer Time: 41:43)) the noise transfer function.

I mean, let me explain what this graph shows. This shows 2 noise transfer functions; the NTF in red has a higher order, then the NTF in blue. Clearly, both these noise transfer functions have the same.

Student: Out of band.

Out of band gain, correct. But in band one of them is doing better; which one is doing better?

Student: The higher order red is doing better.

The red one is doing better, the higher order modulator is doing better? Why do you think this make sense? From the discussion, we just had about this Bode Sensitivity Integral.

Student: Because it has more area.

Ok.

Student: Above 0 degree, it has more area.

All right. So, I mean you can see that the, I mean clearly the area above the 0 dB line must be the same as the area below the 0 dB line, correct. In a high order modulator you can make the transition very.

Student: Sharp.

Sharp. This is exactly analogous to I mean your digital, what you have done in DSP, right. If you have a higher order transfer function, you can make it.

Student: Sharper.

Sharper. You can see that the lower order transfer function wastes a lot of area in the transition. Whereas, if you had a higher order NTF; since, the transition is sharper, right you do not need to waste that area in the transition. At all the positive area for example, can be utilized to get a larger negative area which all happens at.

Student: In band.

In band frequencies, you understand, ok.

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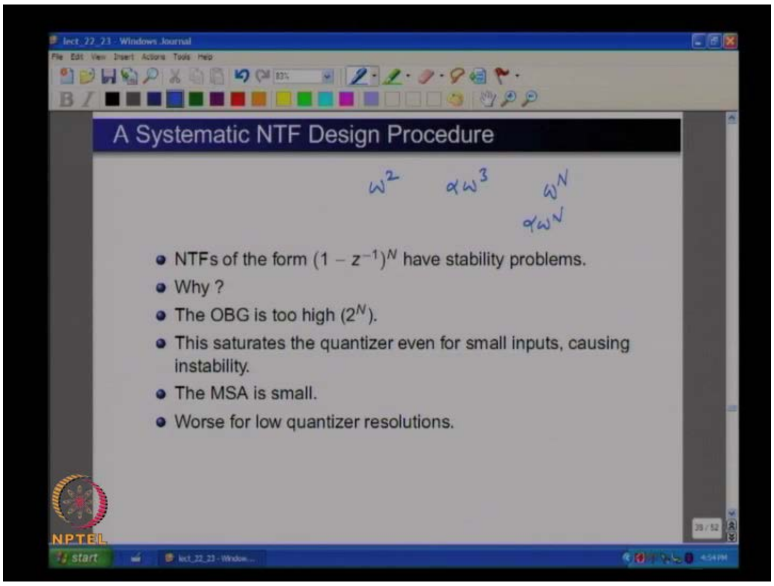

So, that is another piece of intuition. So, to summarize the discussion; so far all noise transfer functions of the form 1 minus z inverse to the N have stability problems. And, the reason is that the out of band gain is too high. Fortunately, this can be remedied by.

Student: Moving the poles.

Moving the poles all from z equal to 0 to locations which are closer to the zeroes; thereby, bringing the out of band gain down and this automatically means that the in band gain will go.

Student: Up.

Up somewhat; because the out of band gain and the in band gain are related and you cannot do better out of band without making things in band worse, all right. So, we now at least have a way where; yeah sure, we have a high order NTF right. But the I mean instead earlier we had an NTF with say omega to the power N with very small MSA. Now, you have some alpha times omega to the power n, but the MSA is much larger, right. This alpha being greater than 1 is not really an issue because going from, I mean the what is the whole idea in going to high order modulator? You want to reduce the in band noise, correct; all right. So, let us say you had for second order you had omega square, third order we cannot have omega cube; you must have some alpha omega cube where alpha is greater than 1, right. So, compared to omega square alpha omega cube is much smaller, right; because at low frequencies omega is virtually.

Student: 0.

0, right. So, the increase in quantization noise due to alpha being greater than 1 is much smaller than the reduction in the quantization noise because of the extra factor omega, right. So, it does indeed make sense to go for a high order modulator which of course, has been designed. So that the maximum stable amplitude is not is not very small. And, that is done by moving the poles, choosing the poles properly; so that the out of band gain is smaller than 2 to the N correct.

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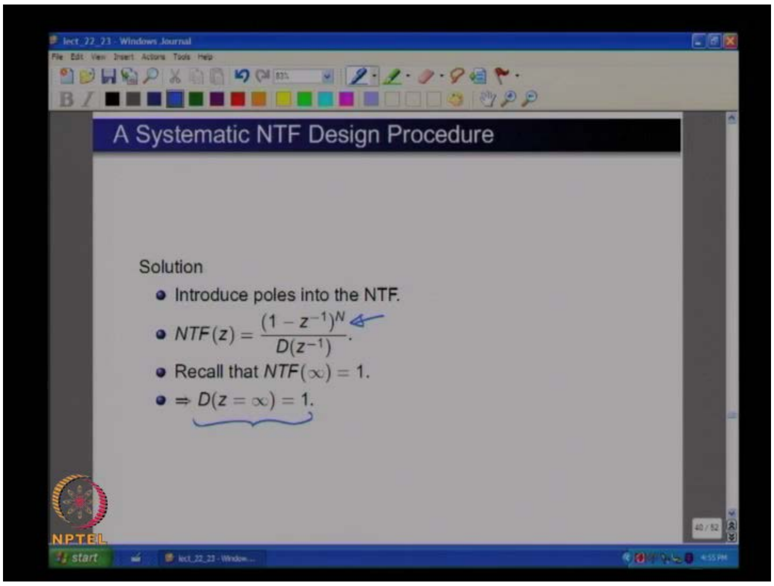

So, let me quickly go over a systematic way in which one can design an NTF, all right. So, as we said we introduce poles, the noise transfer function is now of the form 1 minus z inverse to the N divided by D of z inverse, right. So, D of z were evaluated at z equal to infinity must be 1 and as we saw the out of band gain will now reduce because of the moment of the poles. The in band gain will go up and that is not a problem as we just discussed.

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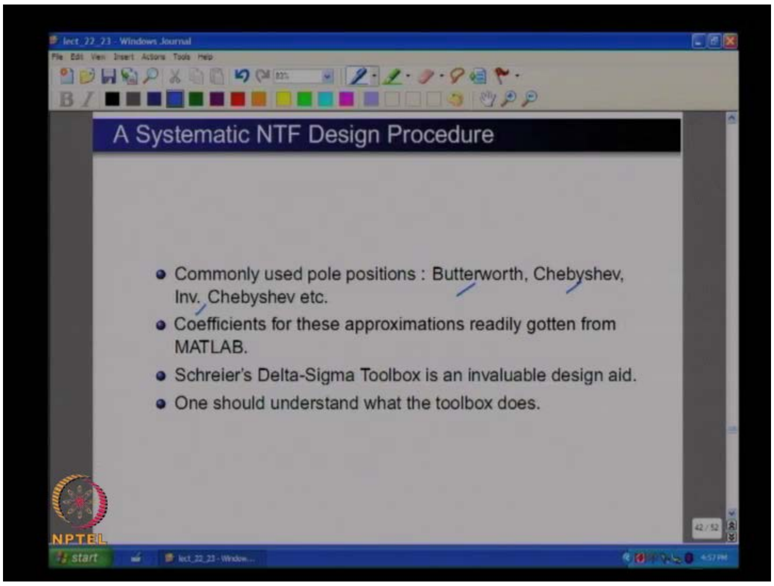

So, the systematically design an NTF, what? one realizes is that a noise transfer function is nothing but a high pass filter. So, the job of designing a noise transfer function is analogous to that of designing a proper high pass filter. But can any high pass filter be a noise transfer function.

Student: No.

If I gave you a high pass filter transfer function and said this is your NTF; what check will you run to make sure that this is indeed an NTF?

Student: ((Refer Time: 47:48)).

You must make sure that the high pass filters response, that the transfer function when evaluated at z equal to infinity must be 1. Otherwise, you will not be able to realize it. Because you for realization, you must have a, you must not have any delay free loops. So and high pass filters you know they synthesis and approximations are being worked out, they are all well known stuff. So, it does not make sense for us to start inventing new high pass filters. We actually take resort to MATLAB; where you know all these libraries are been around for ages, right. So, you put your favourite high pass filter. Let us say one of you likes Butterworth, one of you likes Chebyshev, one of you likes inverse Chebyshev, but does not matter; you pick a high pass filter family, all right.

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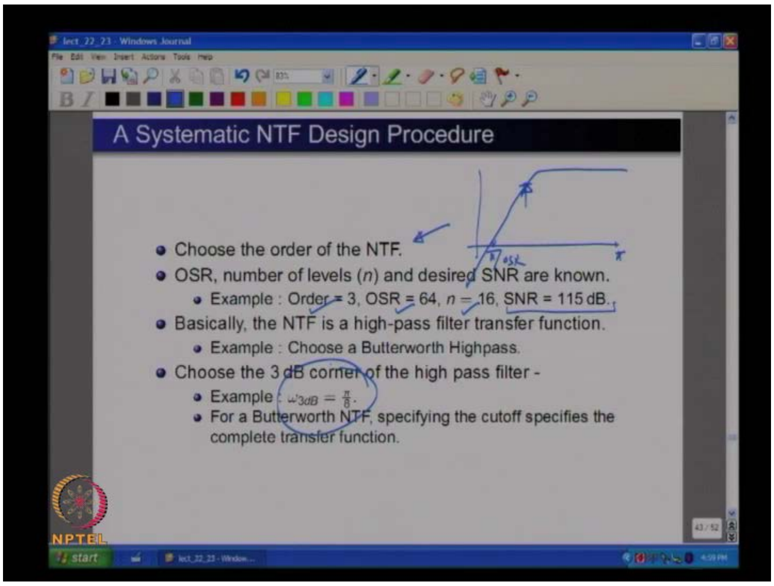

And, I mean. So, when you starter starting off; let us say you choose the order, right. You choose the over sampling ratio, right and you choose the number of levels in the quantizer. And, you choose the target SNR; this SNR is the.

Student: In band.

In band signal to noise ratio. So, as an example let me say I like Butterworth. So, I will say I will choose a third order Butterworth high pass filter. So, once I say that my high pass filter is Butterworth and is of third order there is only one degree of freedom and what is that?

Student: Cut off frequency.

There is only one, you know free variable; that is the cut off frequency, correct. So, since I do not know anything, I will just fix some random cut off frequency, right I mean. So, this is my pi, this is my signal band pi by OSR. The cut off frequencies of Butterworth; can you comment on? Should it be greater than pi by OSR or smaller than pi by OSR?

Student: It must be much higher than.

It must be much higher than?

Student: Pi by OSR.

Pi by OSR. Because the high pass filters transfer function is like this, correct. You do not want to pick a cut off, I mean this is the cut off frequency, correct. And, your signal band must be in this top band of the high pass filter. So, it make sense to choose a number which is much higher than pi by OSR, right. So, I randomly chose pi by 8, all right.

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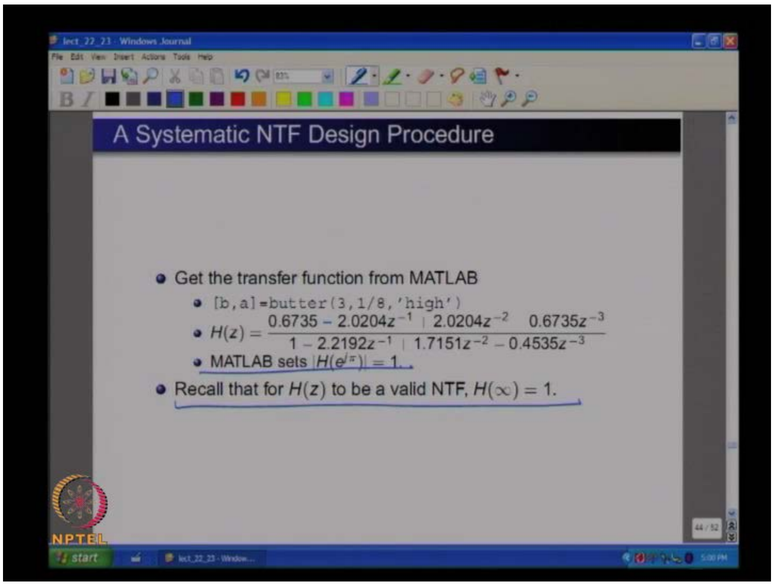

And. So, you get the transfer function from MATLAB. MATLAB, unfortunately I think this picture is missing the minuses and pluses. So, anyway MATLAB does not know that you are a sigma delta designer, right. So, if you ask it for a high pass filter, it will give you ratio of polynomials such that the gain at in the pass band is.

Student: It is 1.

It is 1 correct. So, unfortunately or I mean whatever; so, but we do know that for a valid NTF H of infinity has to be plus 1. So, what do you do?

Student: Divide it by ((Refer Time: 51:19)).

You just have to divide the first term; make sure that the first terms or the constant terms in the numerator and denominator are of both 1, ok.

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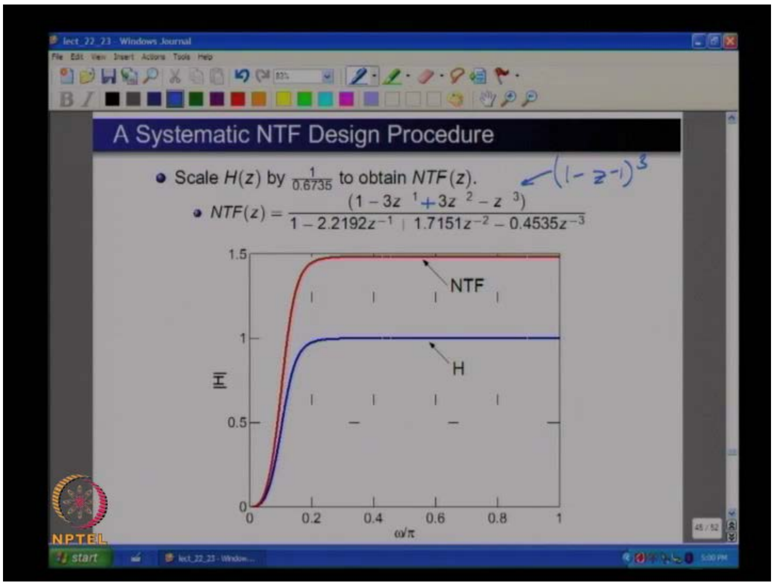

So, once you do that you will get and NTF where the numerator must be of the form 1. This must be 1 minus z inverse the whole cube, because a Butterworth filter has got all it is zeroes at z equal to 1. Butterworth high pass filter will all, will have its zeroes at z equal to 1. So, if the original H the high pass filter that MATLAB gave you was like this. Once, you scale the coefficients, you will get a noise transfer function whose magnitude response looks like this. In the next class, we will continue and see how one goes through the systematic design procedure.

Thank you.