INDIAN INSTITUTE OF TECHNOLOGY
KHARAGPUR

NPTEL
ONLINE CERTIFICATION COURSE

On Industrial Automation and Control

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Topic lecture – 17
Time Delay Systems and
Inverse Response Systems

A very good morning to you today we are going to look at lesson number fifteen of this course.

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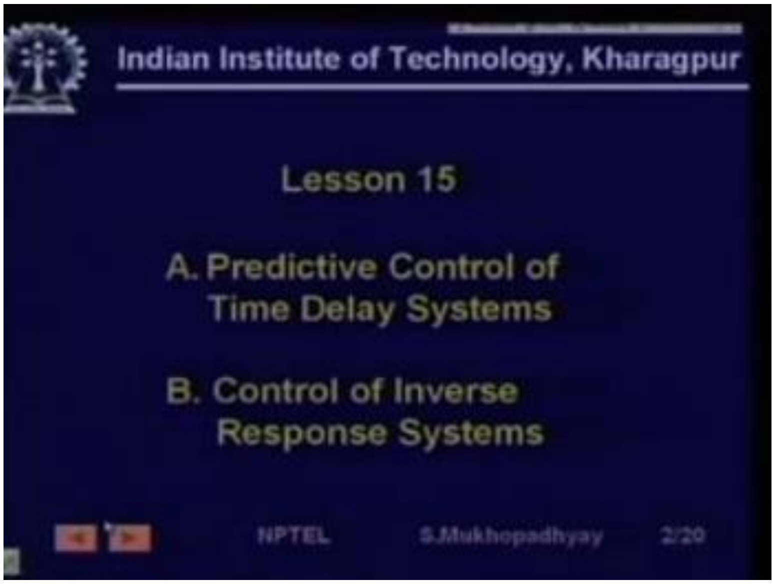

Which is on two topics a predictive control of time delay systems and control of inverse response systems so we are going to look at two typical kinds of processes which I would rather say two special kinds of processes which arise in the industry in various context and we are going to see special configurations for controlling these processes, so as is our practice will first look at the instructional objectives for this course.

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Which are number one first of all we need to understand how time delays arise in industrial processes and then we need to understand why what is the effect of this delay.

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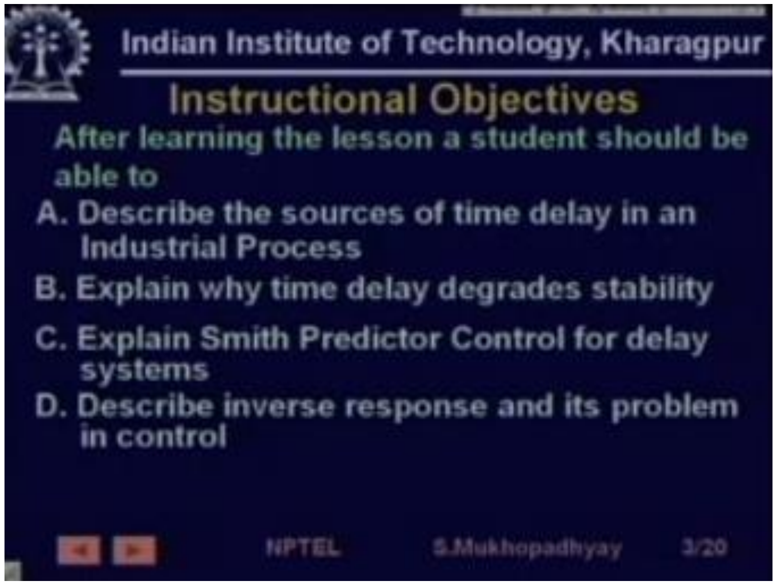

And why it generally degrade stability and creates problems and finally in the context of time delay we have to understand where to look at least one way of one effective way of controlling it and see what it involves similarly for inverse response processes we have to first of all know what is inverse response and how it arises and at least an example and what kind of problems it caused in control and then see.

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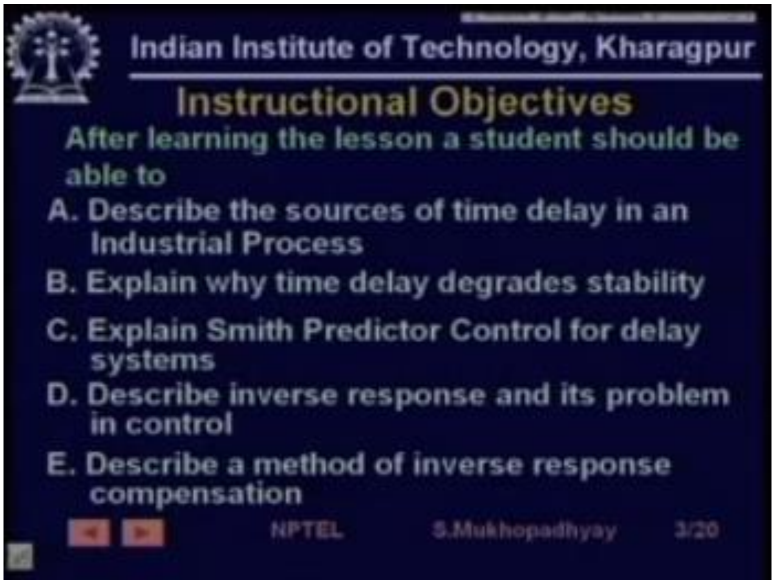

One method again of inverse response compensation, so this is what we are setting out to learn today so let us first look at the causes of time delay.

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The main cause of time delay is transportation lag this is the most common and prevalent type of cause for time delay because in the industry material has to be transferred from place to place in the course of operation and material transfer flow of liquids movements these things take time so there is this is the this is called what is known as transportation lag and is causes you know the majority of the cases where time delay is seen especially in process control chemical process control the majority of the cases is due to this transportation lag.

So this transportation lag can cause a delay either in a process because things have to be transported from one end to the other for example suppose you have a distillation column so if you want to have composition control and if you give an input let us say either at the either increase the let us say the re-boiler heat input then the effect of that input has to has to travel that is the which will lead to a temperature change in the material then that has to physically travel up and down that is a vapor has to travel up and the liquid has to travel down.

To finally effect composition so this essentially involves a delay similarly in the case of an actuator you know actuators typically let us say again let us let us take the case of temperature control temperature is controlled by sending steam heated steam around jackets of reactors let us say one way, so if you give an input that is if you increase the steam flow rate by giving a commanding a valve then that increased in flow rate must let that steam must travel and fill the jacket for the transfer to actually take place right.

So therefore this transportation lag causes delays both in the process and in the actuator similarly apart from transportation lag there are situations.

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Where delays are caused also in the sensors for example sometimes you have you know especially in composition control sometimes you have instruments analysis instruments called analyzers in the loop so they will give you various properties of liquids percentage of a particular ingredient of the composition I mean something like a gas chromatograph and these instruments by their very nature they sometimes involved delays.

So sensors can also involve delays there are there is another class of cases where you know sometimes sensors for example nowadays in the industry a lot of camera based sensors are used now camera based sensors involve lot of computing that is image processing related computation to give the result so sometimes these computations involve a certain kind of delay right in the typical factory context it is it is often not significant this kind of delay but in other especially for electromechanical contexts where you need to control at a high speed sometimes this delay could prove non-trivial.

The third very interesting case where something where a delay may be caused is because there is a human in the loop you know apart from coming little aside from industrial example one of the classic examples of a human in the loop control system is a car so car and the driver who is the controller so he gets his feedback from his eyes and he reacts by giving control inputs to the car for example if he sees that the brake lights of the car head lights up he sees this and jumps the break.

So because of inherent human reactions this sometimes involves a certain amount of time called the driver reaction time and in fact this is what in transportation engineering this is a factor which will eventually decide what can be available or safe velocities of cars and safe distances that they must maintain at that velocity so humans in the loop can sometimes also cause delays now what are the effects of off of time delay.

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Let me tell you that I mean how time delays caused problems for example I will tell you I will share with you one example of mine have you seen you must have seen some modern bathrooms where there is a where there is a there is running hot and cold water supply so usually typically you cannot address I have not seen a bathroom where you can set the temperature of the mixed water.

What is generally provided is a hot water is a is hot water tap whose knob you can turn and a cold water tap now suppose that you want to take a shower and you want the tech water at a certain temperature so what are you going to do you are going to set up a control loop how you are going to you will probably the safe way of doing things is to turn on the cold water to the maximum.

And then put your hand in the shower and feel the temperature and then adjust the hot water in fact this is what I was doing one day and after some time I realized so I put my hand in the coldwater it was too cold for me so I started turning the hot what a tab so I was turning, turning, turning and then suddenly I found that the water is too hot and then I started turning back and then suddenly I found that the water is too cold.

After I was doing this unmindfully and after two three cycles I took notice of this fact that what is happening why am I not able to set a particular temperature but rather always either exceeding on the positive side or the negative side and then it suddenly dawned on me that wow here is that this is a case typical case often of an oscillating process control loop and why was it happening why was the loop oscillating the loop was oscillating.

Because there was a delay between my turning the knob and the and the water actually coming on to my hand because it had to travel through a pipe so here there is a transportation lag there was no lag in the sensor because compared to that delay the delay in filling the temperature was negligible but coupled with the fact that my controller gain was very high you know typical taps which you have in the bathroom or quick opening kind of valve.

So that you can buy a small turn of the knob you can increase the flow rate very fast and then I was also impatient in the morning I had to go somewhere so I was very quickly moving them out so my controller gain was very high and there was a delay in the loop, so in effect what resulted was an unstable process loop which was continuously oscillating so this is exactly what tends to happen in a process loop if the controller gains are high that it will tend to oscillate.

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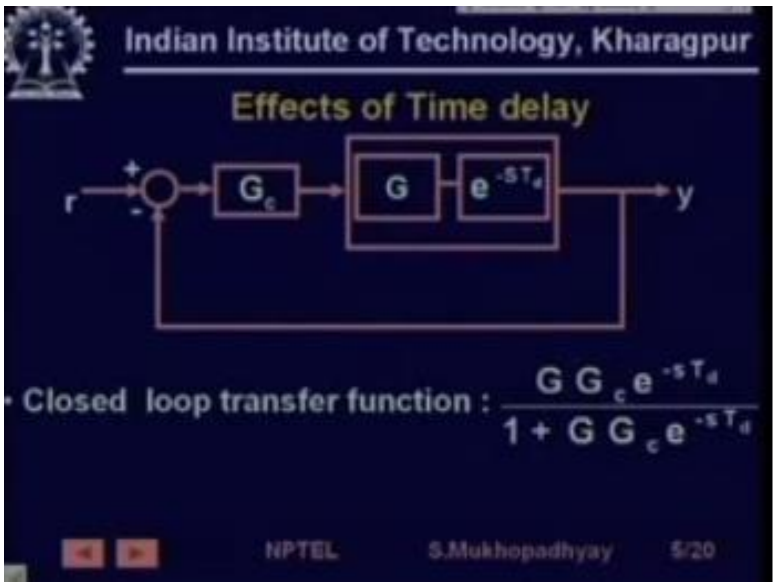

So now let us analyze this phenomenon little more technically so here you have this is the standard process control loop where you have where you have this is the controller and this is the plant and this is the delay that I am talking about and there is a normal process control loop okay so what happened let us look at what is the closed-loop transfer function oh right close this then so what is the closed-loop transfer function.

So the closed-loop transfer function is very obvious that is a GGC E^{-std}/ this is the delay so let us let us try to look at this transfer function and understand what is happening first of all we notice first thing let us notice that in the steady state how can you get the DC or steady state transfer function just by setting in most cases not all cases but in most cases you can get the steady state behavior by setting s is equal to 0.So if we set s is equal to 0 respective of the time delay.

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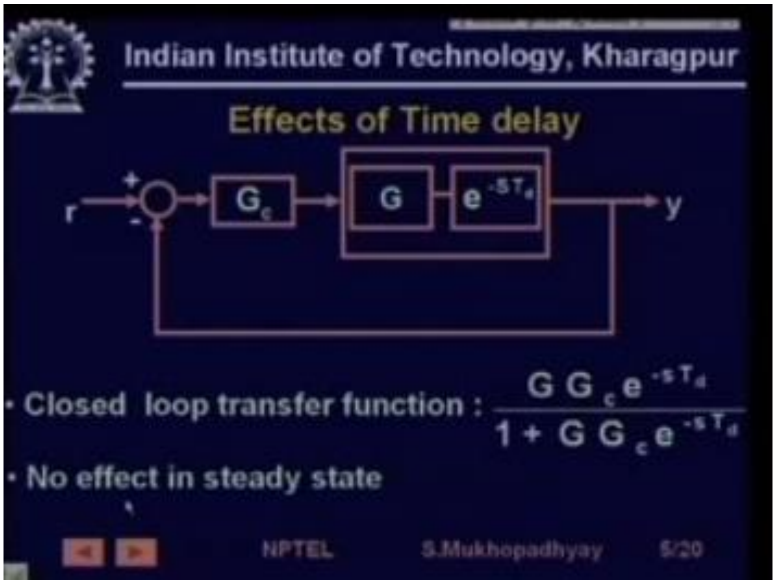

This transfer function will become GGC/1+GGC so the steady state transfer function is not affected by delay right so this is the message that in steady state delay has no effect but as we have just seen that it has an effect it does have a have an effect in the transient state that is when set points are changed or when disturbances occur it is going to have an adverse effect and it is during these times that the process must may start to oscillate right.

So let us try to that is what we want to study try to understand so let us look at this same transfer function.

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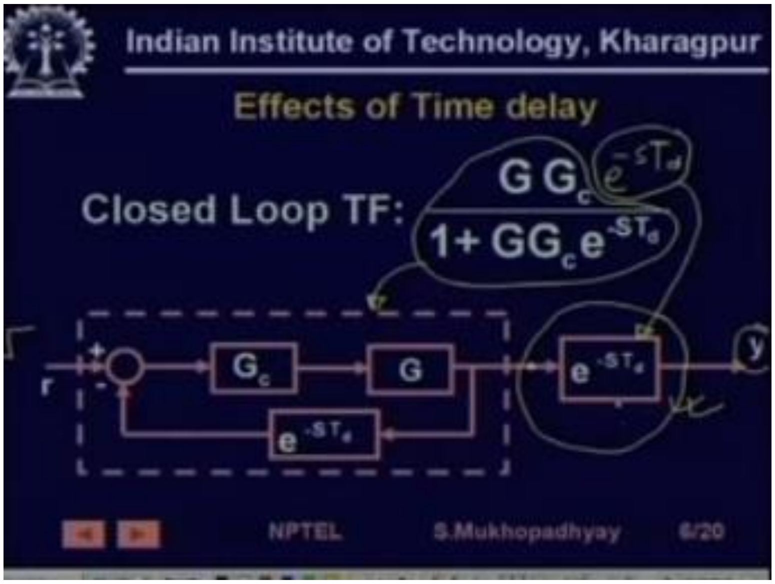

In a slightly different way so the same transfer function I have now I am not looking at the loop in a different way this was a transfer function initially our transfer function was GGC E^{-std} ,so now this E^{-std} if I take outside then this part of the transfer function can be represented by this block so you see that so now this closed loop transfer function we can represent in a in a in a block diagrammatic form in this manner that there is a delay which is going to be caused in the response if you give a step input there is no way that the that the output will start moving immediately.

And we cannot do anything about it is the inherent characteristic of the plant on the other hand now this plant apart from the delay how is this plan different from the delay free plant with which we can do ordinary feedback control so firstly it is different in the way that there is a delay caused in the output now a delay is a delay which cannot be avoided but nevertheless this delay is not going to cause any problem in stability simply the response will be delayed by an amount TD which cannot be helped but it is this delay.

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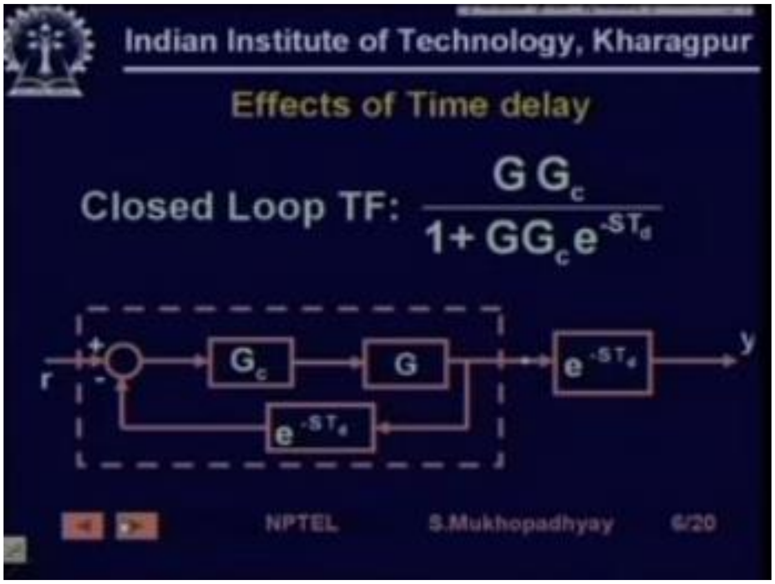

Which is going to cause problem in the stability because it is going to add to the loop phase right this is minus STD so it is going to add loop phase lag and it is this that is going to cause the problem now you see that how does it cause the problem so to understand that let us first notice that in the delay see free process this would have been a director so in that in the delayed process we are going to add additional loop phase delay without adding anything to the loop gain because the magnitude of this operator is always one only there is a phase lag so having noticed that.

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Let us so this adds to loop fast phase lag and therefore here is the comment which will see in greater detail that it reduces gain and phase margin so how does it how does it reduce gain and phase margin we will see that it also says that the that the gain has to be limited to avoid instability obviously if you are if you if your gain margin is reduced then the allowable level of gain becomes lower. So you must use the lower gain now whenever we know that whenever we use a lower gain.

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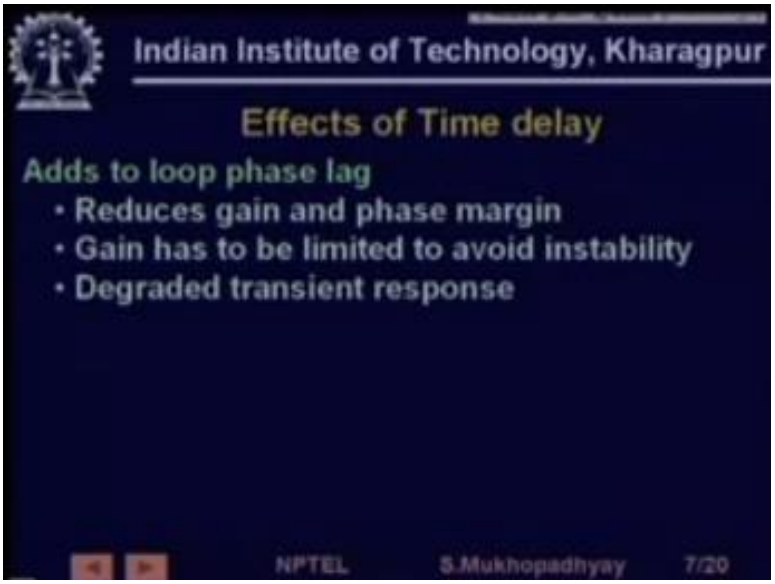

The problem that comes is that you have a degraded transient response in some cases for example if you if you are using a proportional controller and if you use is use a smaller gain then you are going to get greater steady-state error because in the steady-state delay has no effect but if because of stability reasons you one has to use a lesser value of K, then that lesser value of K is going to cause this causes greatest steady-state error which is a which is a degradation in performance. So this is the major problem of time delay but before that.

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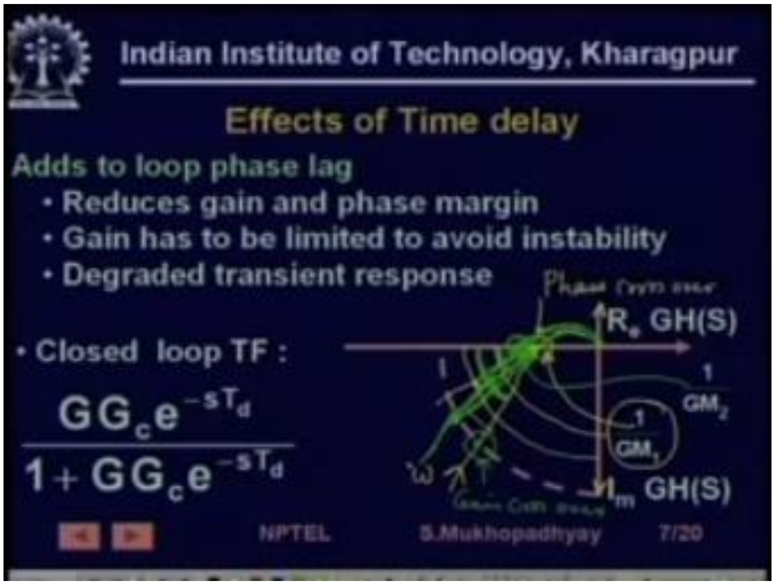

Let us see how this gain margin and phase margin is reduced imagine that the original plan or not original plan that the plant suppose the transfer function GG_Ce has an or rather the transfer function has a Nyquist plot like this okay. So in this direction as we know Omega is increasing so this is the increasing frequency direction these are the two axis this is the real axis real rather this is the imaginary axis and this is the real GHS axis okay.

So this is generally what is called the phase crossover frequency so and it is this frequency this is if the gain here is GM then the gain margin is 1 by GM 1 so this is that of the loop without delay now if you have a loop with delay then what happens what happens is that at every at every frequency now and magnitude will remain same and the phase lag and there will be a phase lag added so if you add constant magnitude low sigh and suppose at this frequency so phase lag will be proportional to frequency.

So suppose at this frequency this much of phase lag is added so at this frequency which is higher some other phase lag will be added this phase lag will be added here this phase lag is added here more phase lag will be added so in other words now the plant will follow a different trajectory so it will follow a trajectory like this so now let me put a different color so that we can understand this phenomenon we have to put and let us put a green color.

So now the new plant with delay flows through the green line so it has got shifted because of the delay so now what happens so now your, now the phase margin has reduced previously what the phase margin this was the phase margin that is the phase at the this is called the gain crossover frequency so the phase margin was this angle now the phase margin is reduced and it is this angle so it is this angle now.

Similarly the gain has increased so now the gain margin is reduced so this is if GM 2 is again then one by GM two is the gain margin so that has reduced so this is how the system is gradually coming closer and closer to instability and therefore the maximum gain that you can use for the plant which is represented by the yellow line the plant which is represented by the yellow line this yellow line and the plan which represent by the green line you can use a lower gain right so this is what happens this is why gain has to be lowered to avoid stability and that in turn causes problems in the response. So this is the point that I was trying to make.

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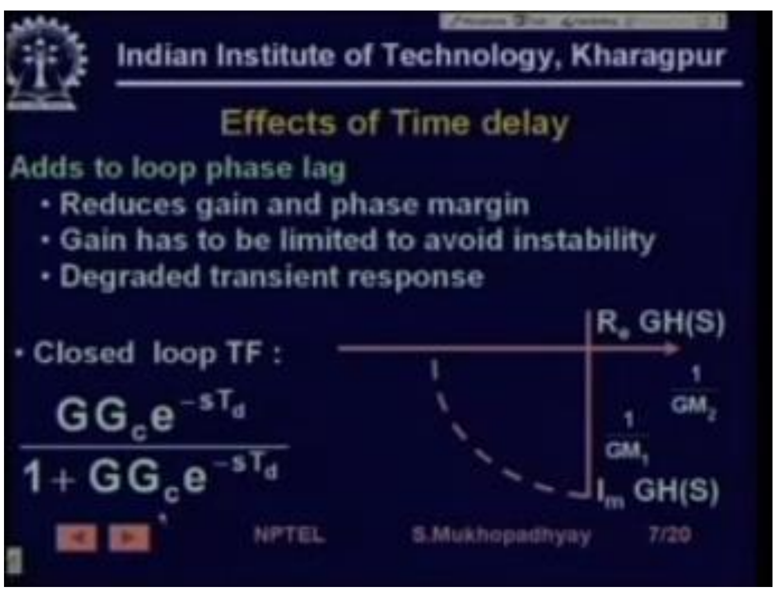

So having said that let us go back to our discussion so now.

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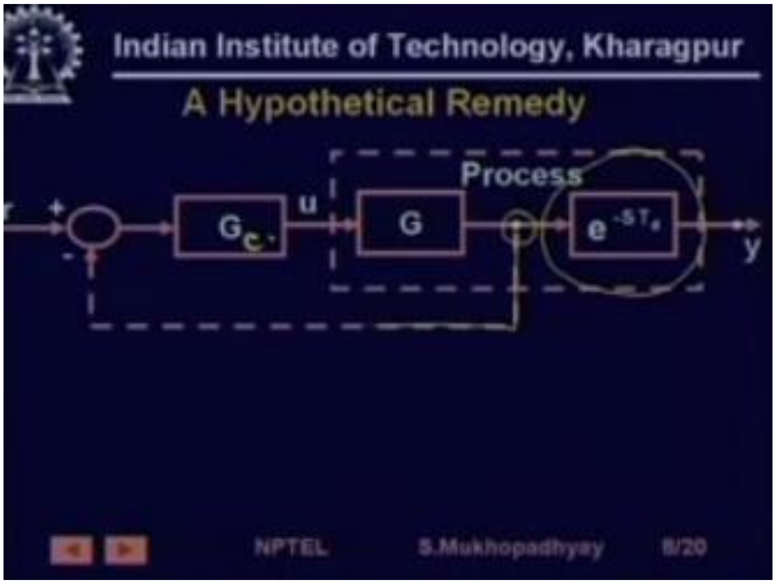

What is that with that we want what was what is a so let me present a hypothetical remedy that it would have been very nice if I if this delay is anyway not possible to remove as such but if somehow we could take the feedback of the process from this point then at least the stability part of it would have been like this is this is GC by the way then at least the stability part of it from the stability point of view the effect of delay I could neutralize apart from the fact that.

In the response there will be a delay that is generally not known order not of too much concern in industrial process control because they are generally I mean whatever response you want it will come a little later that is not so much of a problem but what is the problem is the change in the feedback loop.

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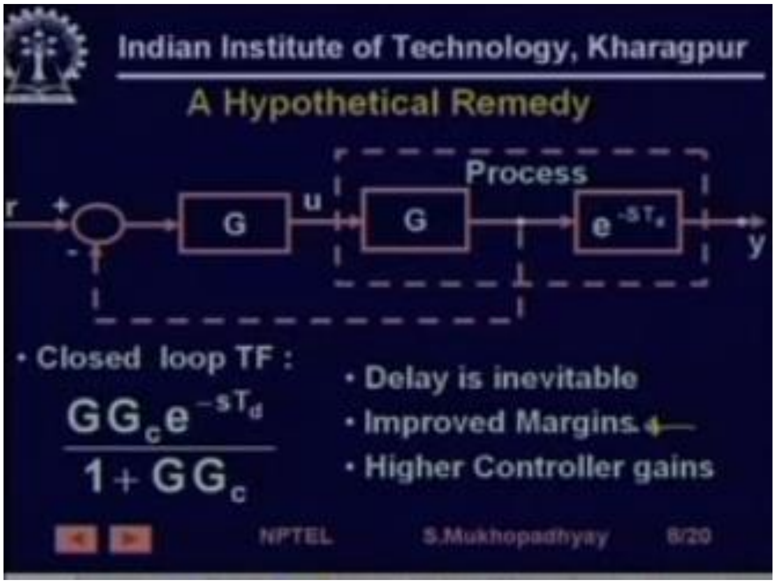

So somehow if I could take a feedback from there but I cannot take a feedback from there because it is within the because this point is inside the process and it is not measurable in fact it is a it is an intrinsic part of the process right so since this point is not measurable that is why this solution is high positive because we cannot take a feedback actual feedback but here comes that, so now if we could do it then I could have much more improved margin.

I could have improved margins like the like my old case so my margins remains would not have do not degrade and therefore I can use high controller gains and therefore my responses would be like I can use higher controller gets that I can improve transient response without worrying about the additional stability constraint imposed by the delay so that is the problem.

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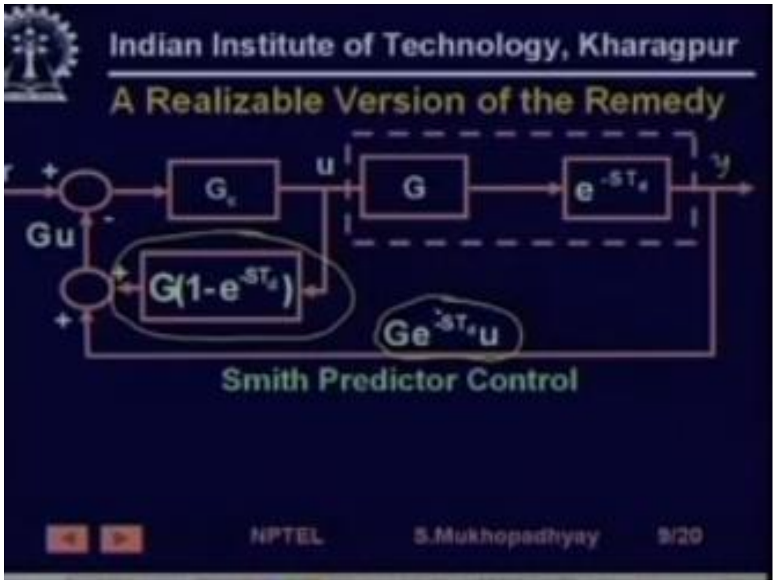

So then how am I going to do this so to do this let me prove it a so called realizable version of the remaining so now what I am going to do is this so you see I am giving the original feedback which I was giving normal feedback and apart from that I am giving an additional feedback so what is this typically speaking in the ideal setting y = g x e^{-stb} x U correct so this is G x e^{-stb} x U and on the other hand now you see that if this is a big if but if I knew G&TD very accurately then there is no reason.

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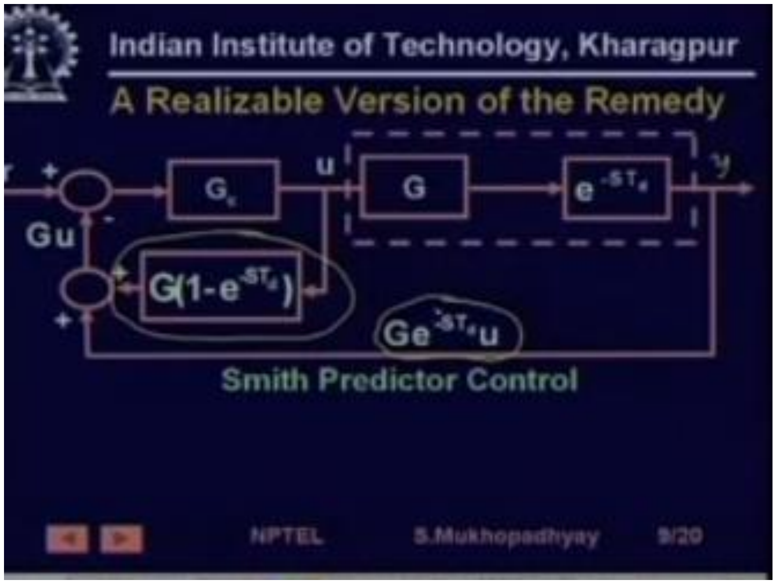

Why I cannot simulate this transfer function and then feed it by U, see U I have because it is coming out of the controller so I already have it controller is in my machine only and if I knew the model so about getting U there is no problem but about getting.

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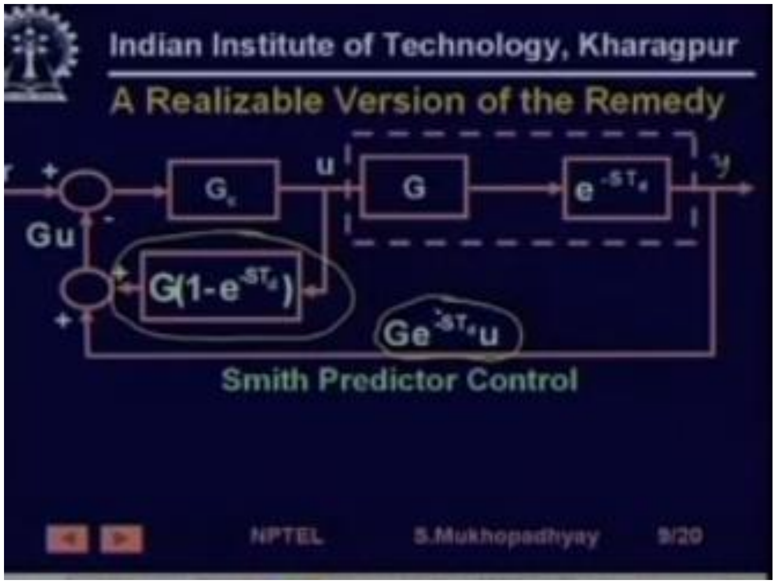

If I knew G and if I knew this TD these are these are questions how well you can you can get them but suppose for the time being that you have it then we could put it here and then.

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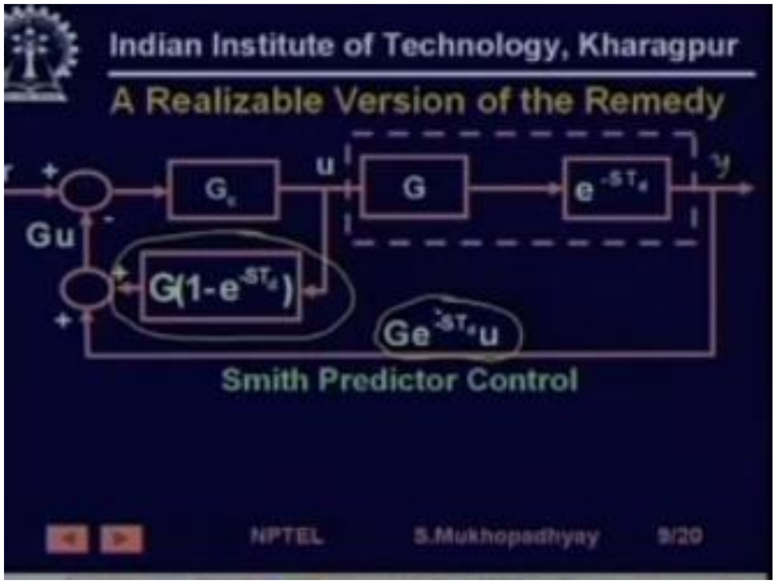

You see if I if I add this and this what do I get I get GU so as if so what is GU, GU is the signal here this is GU so by adding this term I am creating a situation as if I am able to make a virtual feedback here that is what I wanted right so if I do that then I will be able to use my use the use the kind of gains that I can use for the system without delay so this is the basic principle of smith predictor control.

So what am I trying to do why is it called a predictor why is it called a why this term prediction because I am trying to gain effect I am trying to predict the output why because this is Y.

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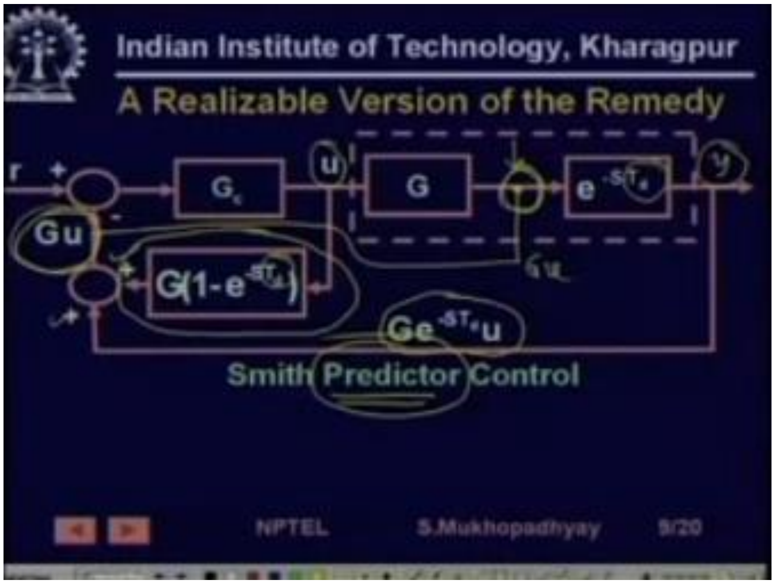

This is the output and what is this is nothing but a future output which will appear here in the measurable form after time TD so since I am so I am trying to recreate that so in other words I am trying to predict the output and then give it feedback that is why it is called the smith predictor control.

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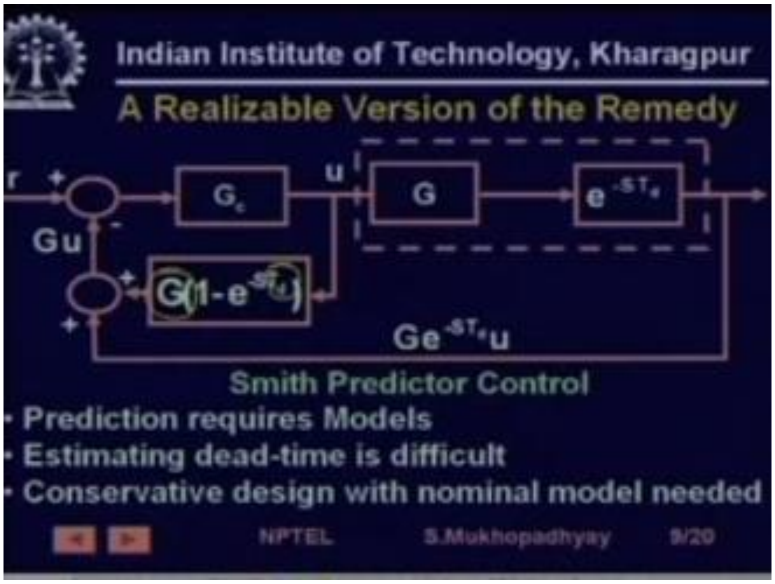

Now there are a score several questions as to how you can do it so the first question is that you require to be able to do it you require this to be known accurately and more importantly you require this to be known accurately you see it is rather it is not so simple to estimate time delays because time delays are often confused with time constants in the response they actually generates similar kinds of response it is very difficult to differentiate between time delay and time constant.

But time delays and time constants differ in a very tangible way what is that way that for time constants for example suppose you have a transfer function called.

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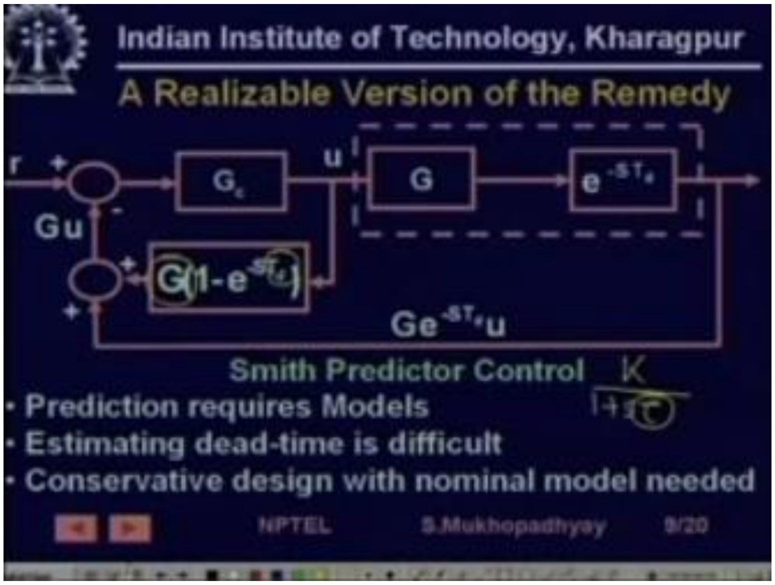

K by 1 plus sτ tau this is at this τ is the time constant so as far as the phase response is concerned let us take a let us take a white page now would it come.

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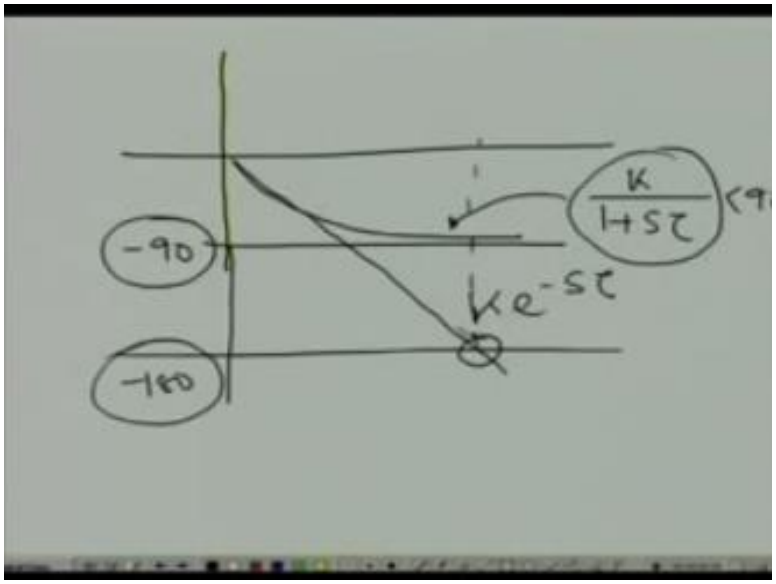

So this K by 1 plus sτ let me choose a different color pain because the background is now white let me choose black so the phase of K by 1 plus sτ is going to be limited to -90 so it cannot increase beyond -90 this is for K / 1 + Sτ tau on the other hand k $e^{-s\tau}$ we will have a phase which is increasing linearly with frequency so there is no bound so this means so for example this system phase will is always less than 90 but this system phase will is at some frequency it is going to cross at some frequency it is going to cross the -180 point which is the critical point for stability.

So the question is that that so there is always this phase lag the phase lack of the process with a delay is always going to cross 180 but the question is what is the gain at that point so to ensure stability you have to keep the gain low at that point that is why you have a limit on the game while in this case in this case.

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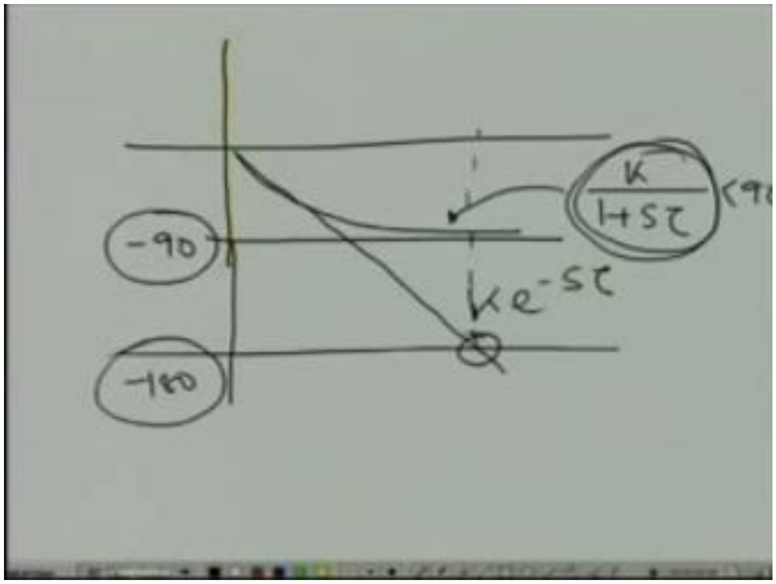

You do not have any limit on the gain so what happens so you see that.

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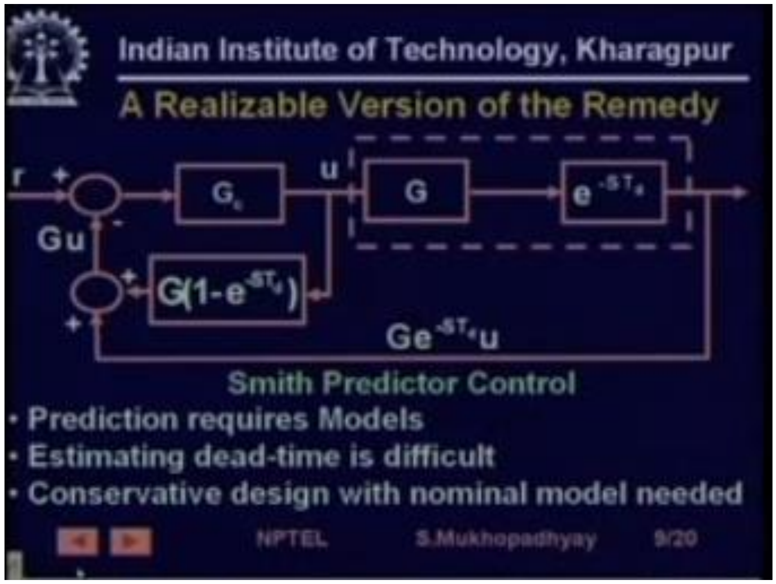

That I mean time constants and time delays are slightly different a time delays are potentially more risky but distinguishing them from time constant may not always be so simple so therefore estimating dead time is difficult.

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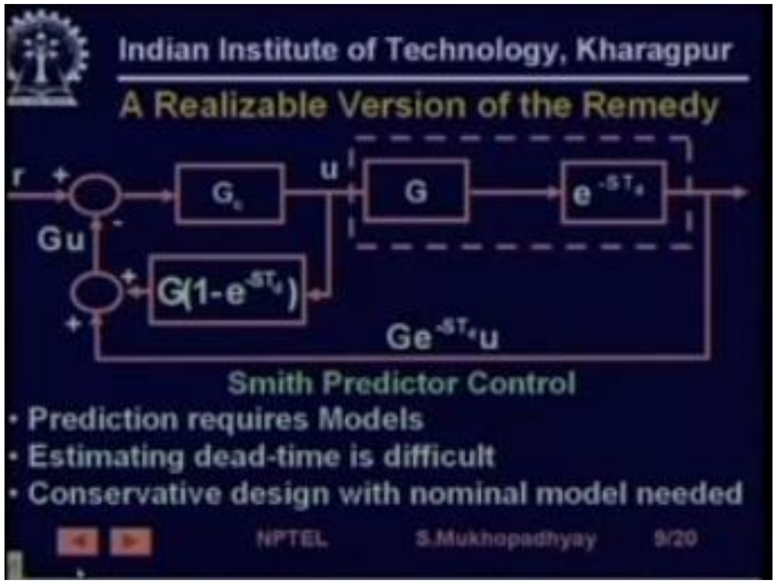

And therefore we must have a conservative design that is if we think that the if we should always design a controller k for a worst-case delay because if the delay is if we design for a best case delay and if the delay is more then we might land up with instability right so this is another problem that as such we have to limit the gain and because of the fact that we cannot estimate the delay accurately in many cases in our design we would we would estimate it conservatively and will further limit the gain because of lack of knowledge.

There may be another case also there maybe cases where the delay maybe very you see the delay is caused by what delay is caused by transportation lag so basically it is a time required for the material to flow at a given flow a given distance now this flow I given distance how much time is required that is the time delay obviously depends on the flow rate now the flow rate depends on what flow rate depends generally on the operating condition of the plant right.

So if I if a reactor is producing is producing something at let us say fifty percent volume then the flow rate will be half of generally speaking it will be half of if it is working at one hundred percent load so they so the time delay will reduce so now depending on various operating conditions the time delay in a process can even vary not only the first of all it may be it may be difficult to assess secondly it may also vary.

So if you are going to design a single controller for all operating points then further you have to always take make a design which is which will hold good for the washed delay so which means that for the for the best case delay you are going to get you may get very poor response so actually these are the problems of time delay systems which is somewhat overcome now how are these thing over come here.

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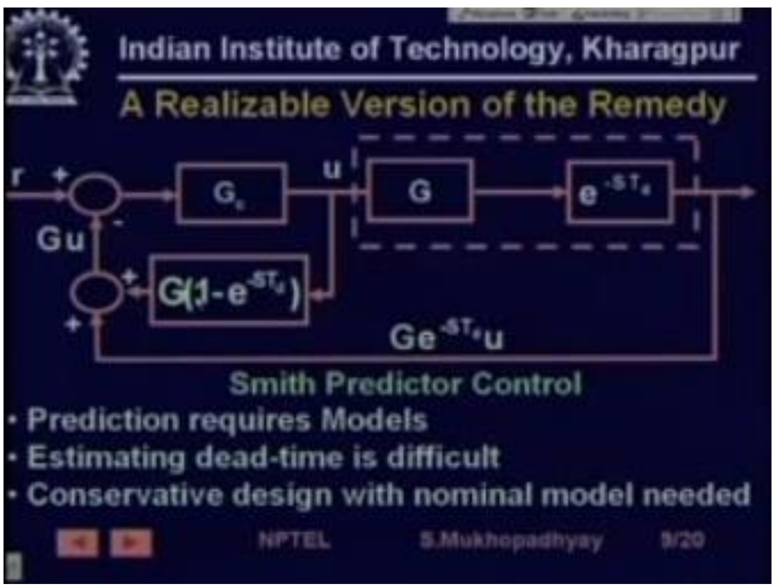

So here also you have to do a year also if this GE and this just a moment so here also if this G.

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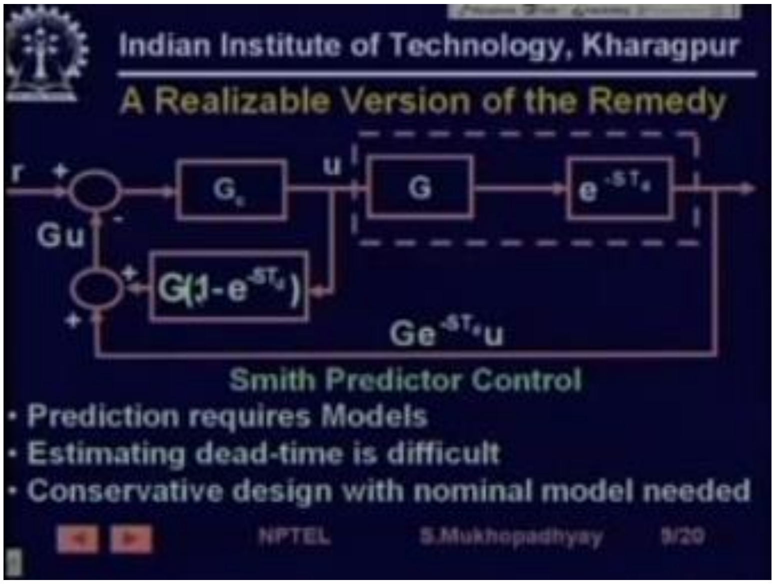

I am sorry if this G and this TD this is such to selected as black so if this G and this TD are not properly known then the compensation that I am talking about will not take place it will take place only partial so here also we have to make a conservative design but at least the situation is better there is one more point very interesting point which I wanted to mention.

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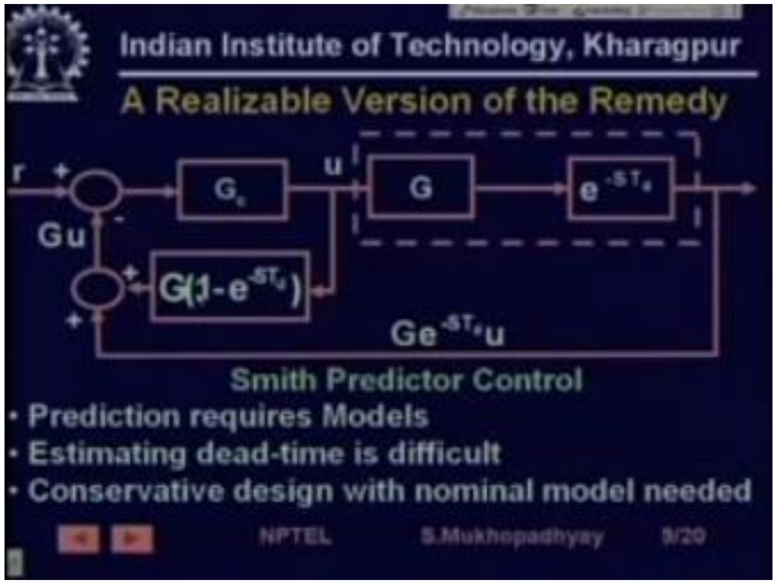

That is the question is that if we want to calculate GU then and we are saying that we need G we are assuming that we know G accurately so if you want to calculate GU and give feedback and if we have U.

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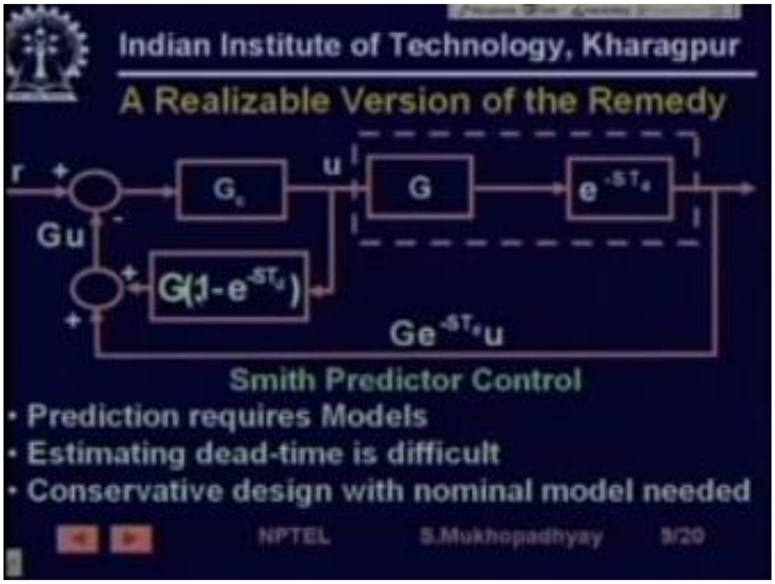

You and we know G so then why do we need this feedback at all why do you read this why can't we just take U and then multiply it by G and then give a feedback that is most simple but what do we get it yet then we get what is known as we get what is not an open loop control there is no feedback what are the problems of open loop control that any error in G will directly affect the output Y any disturbance here.

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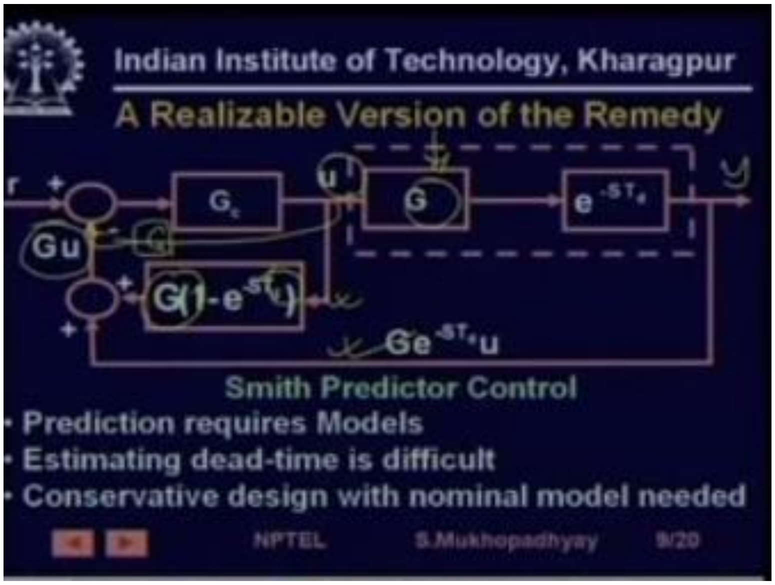

Will not get corrected the biggest advantage of feedback control is that it gives you performance irrespective of generally irrespective of course you have to know certain things but small modeling errors do not affect performance that is the single reason for which feedback control is used and if you take this feedback away.

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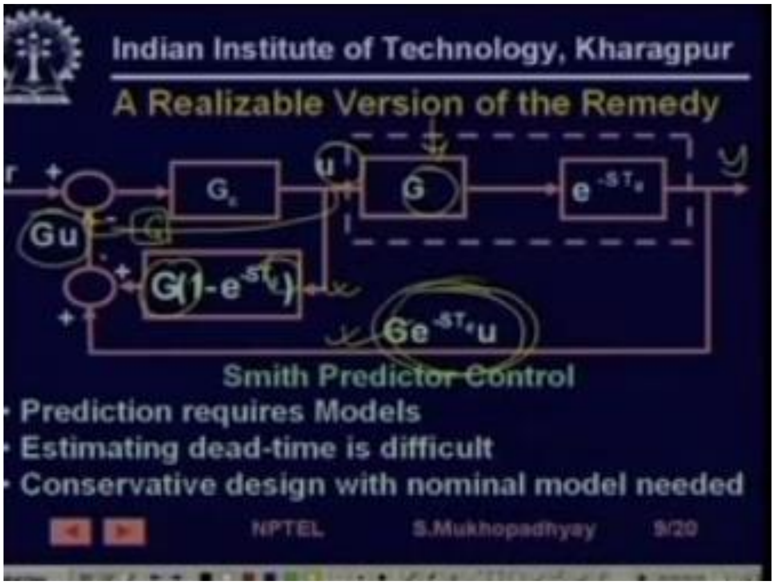

Actually this is not in presence of modeling errors this is not G^{-std}, so if you want to have the benefit of a delay correction according to a model and then also keep your control performance sensitive to modeling errors as well as disturbances then you must feedback measurement.

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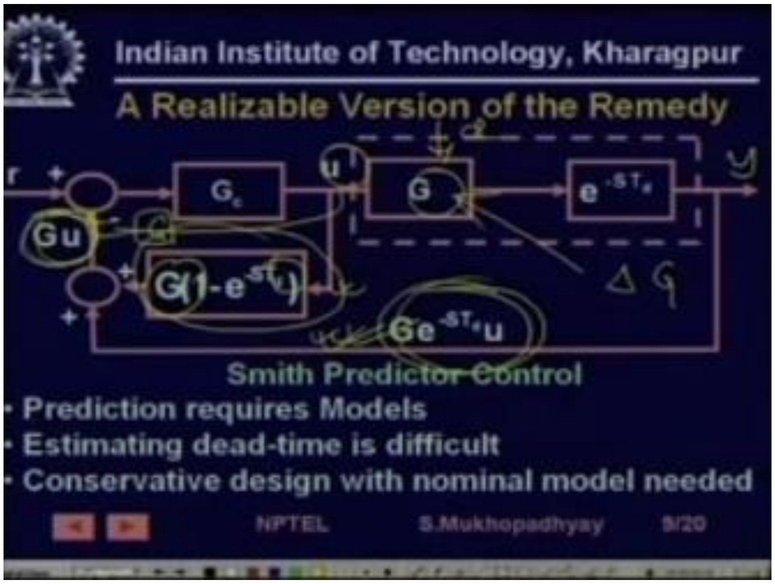

So you cannot just multiply it by G and sin because then you are going to be blind to the actual reality if there is a disturbance that will not be affected here so it is for this reason that although under ideal condition it actually turns out to be GU but in real conditions it will not turn out to be you and it will that is your control loop will not become blind to things such as disturbance things as such as modeling errors ΔG here right.

So it is for this reason that you must keep the feedback and it is for that reason that we have added this term other than taking GU so these things must be these are some you know something fundamental principles which must be realized in control.