INDIAN INSTITUTE OF TECHNOLOGY KHARAGPUR

NPTEL
ONLINE CERTIFICATION COURSE

On Industrial Automation and Control

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Topic Lecture – 19
Special Control Structures

Good afternoon this is our last lesson on.

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Process control today we will look at some special control structures special in the sense that so far whatever controls we have studied PID control, Smith predictor control everywhere the we had sensed one particular process variable which we wanted to control that is the output and we fed it back and we also use only one actuator, now today we will see that in some cases situations arise where we can use more than one sensor in a process.

Or there are sometimes more than one actuator also so we will take a brief look today at those kind of control structures and we will also see what kind of advantages can be derived by these so that is the objective, in particular we will study cascade control.

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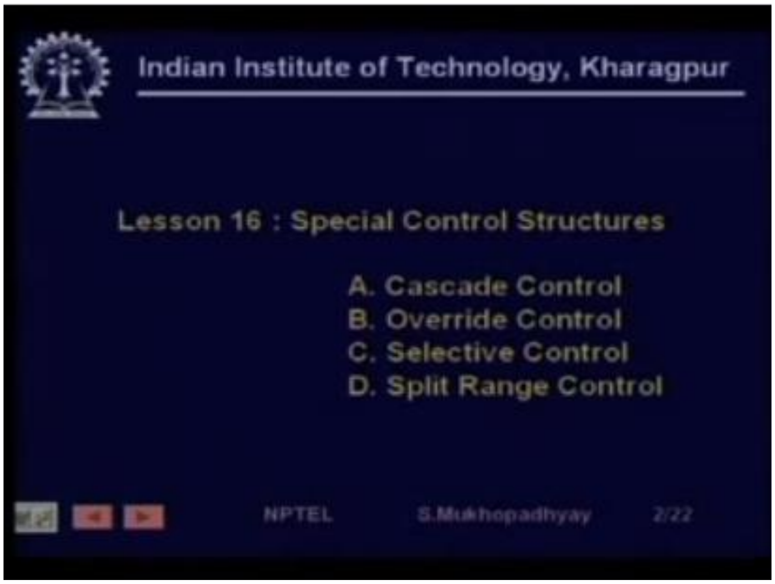

Which is a very popular control strategy we will study something which is known as override control, selective control and split range control these are very standard terminologies in found in process control books so we will take a look at that, right. So before we do that let us first see the instructional objectives.

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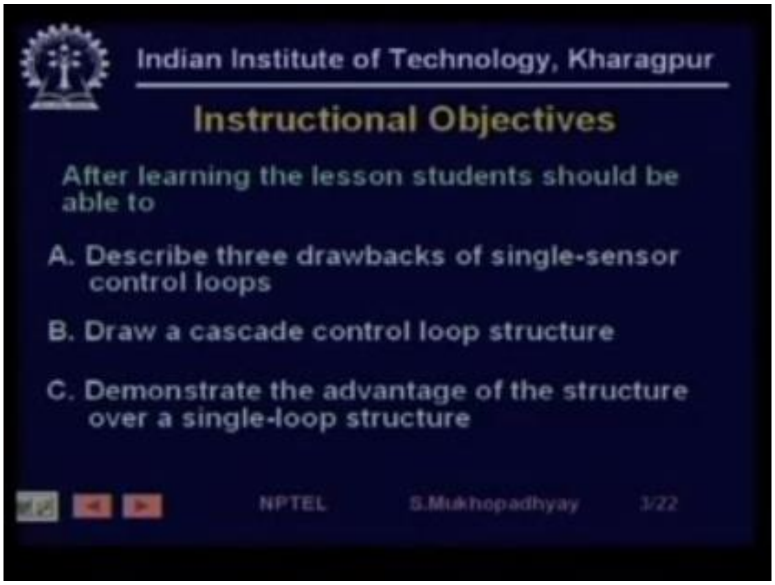

So today after learning this lesson the student should be able to describe some drawbacks of single loop control and based on some of these drawbacks we can see that cascade control will address some of these drawbacks and therefore we will learn cascade control and he should be able to draw a cascade control loop and demonstrate the advantages of this structure over a single sensor feedback loop unconventional.

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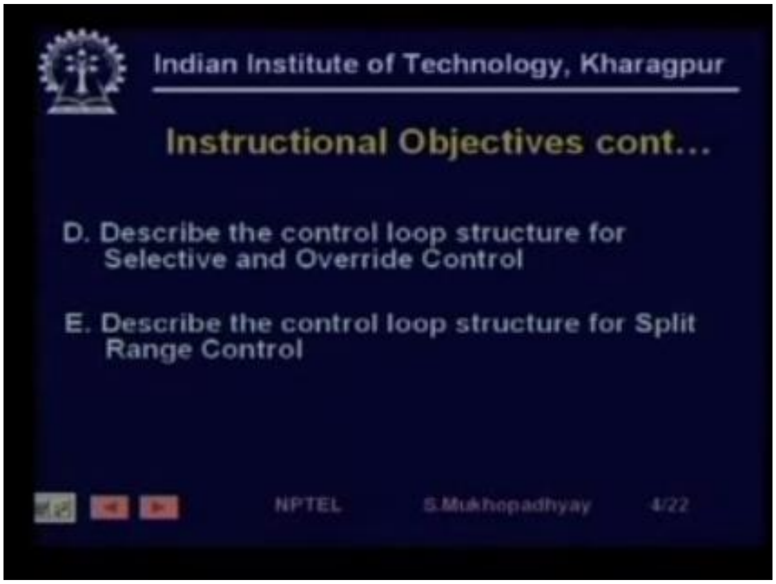

Additionally he will also be able to understand what are what are selective and override controls and similarly for split range controls. So this so the basic idea is to familiarize ourselves with this kind of control loops and understand their advantage. So first we will take a look at the problems of single sensor control loops.

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Sometimes it happens that you know the basic idea of a control loop is to correct or adjust the control input to take care of the disturbances basically there and it and in a standard control loop does it by computing a control law based on the error, so how quickly the control loop will be adjusted in response to a disturbance depends on how quickly the error will be formed so for example we have found that in our in our single sensor control loops for example.

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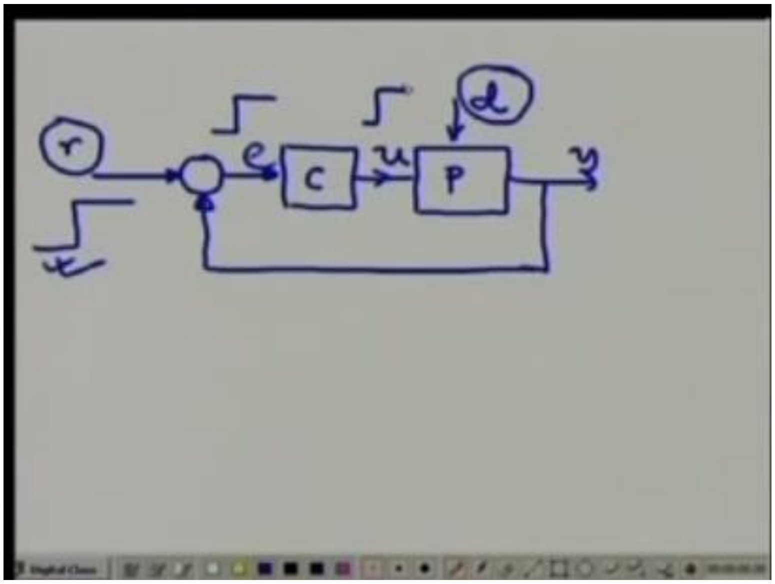

In our let us take the standard control loop so you have the reference coming here and here you have the controller CE and the plant PE and this is the output and there is a feedback, so you see that there may be disturbance is acting on the plant at various points, right. So these are disturbances d this is the set point r and this is the output Y, so the controller basically can calculate this U which is the control input.

To either take care of 22 if to take care of basically variations in either r or d so if r is changing that it needs to adjust U so that y becomes close to R, now you see that this controller does well because any change in r if r changes from this level to this level let us say then immediately the error will also jump from this level to this level, so the change in error E is almost instantaneous corresponding to the change in r.

So the controller also responds with an instantaneous change in u and the output gets adjusted as quickly as possible but that does not happen when there is a change in disturbance level, so because this the even if you have a.

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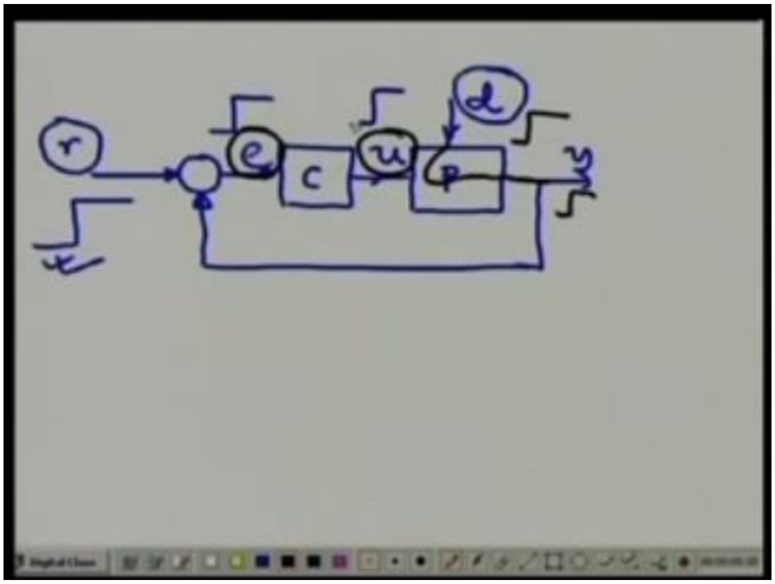

Let us use a different color of the pen, so even if you have a disturbance d changing here the effect of this disturbance to come on the output take some time because the disturbance has to enter through the plant and then travel to the output, so during that time the error E remains unchanged and the controller does not obviously adjust its input, so this is a this is a problem of single loop control, okay.

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So having understood this we can realize this that high lag between error disturbance and an output can sometimes occur depending on where the that is appearing, the next point is that now we know that if there is high lag then our phase margin is low that is the system loop transfer function has lot of phase lag so therefore we need to keep our gains lower to maintain stability.

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Now if we have to keep our gain slower naturally we will get poor transient response so we are not driving the plant hard because of stability requirements, right. So this is the problem which arises in single loop control sometimes.

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Secondly this is a problem which will address you will see how it can be addressed by using cascade control and very commonly addressed now there are some other situation screens control for example in some cases we have to control the a variable which exists over a distributed spatially distributed region for example suppose we want to control the temperature in this room in which I am sitting.

So obviously this room is a big place where I mean how do you control the temperature in a room typical in air-conditioning you provide cold air, now how much cold air you will provide depends on what temperature you want in the room but how do you give feedback obviously using temperature sensors but a temperature sensor will suppose it is a solution RTD typically in air conditioning temperatures are sense using resistance temperature detectors.

So where will you put the resistance temperature detector will you put it on the ceiling or will you put it on the floor if it is on the floor which corner of the floor or would you put it in the center, so remember that you will be controlling the temperature and exactly the point where the where the sensor is put even if the temperatures at the other places are slightly different the controller has no way of knowing that.

Because the sensor is the controllers I, so therefore whenever we are having a sensors we should understand that we are controlling the controlled value at that sensor location, so if you want to maintain some uniform control over region sometimes we need to put more than one sensor and incorporate them in a control loop, so this is the requirement in many cases.

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So therefore multiple sensors at different locations are needed to control the overall process average so you want to control the average temperature of the room so you have to put three four sensors at three four different locations or sometimes we want to control extreme values you know because sometimes the output at various places may not be the same and if it goes too high it may cause damage or if it goes too low it may cause damage.

So sometimes we may we may like to choose average values sometimes we may like to choose extremer values that is maximal or minimal values and for these purposes we need to put multiple sensors, there are also some cases where systems are actually operated in different modes that is when it is in suppose the set point is very low then you want to operate the system in one mode if it is very high you want to operate it in another more.

Typically happens because processes are non linear for example if you want to in if you go to western countries then you will find that part of the year the temperature becomes warm so you need air conditioning or you need cooling and part of the time when it becomes when in I mean in winter you have to heat the room, now you see cooling and heating cannot be done using the same equipment.

So you essentially for controlling the same process variable that is the room temperature use you need two different sets of equipment or actuators and you need to have a control loop which will which will incorporate these two actuators and actuate one any one of them depending on the set temperature that you want that is whether the set temperature is less than ambient or is it more than ambient.

So in such situations sudden changes to the loop structure has to be made and we are going to study that, so let us first look at cascade control so we are first going to look at the error at a motivation for cascade control.

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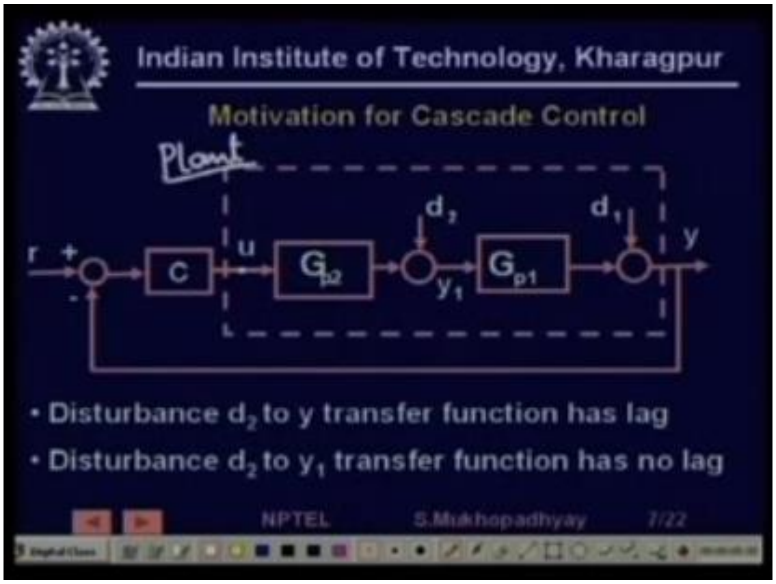

So here we have a imagine a process right so here we have a process so this is our plant now we are just imagining that the plant is actually consisting of two different subsystems, presently we see examples we will see examples very shortly there are many cases, for example cooling of reactors is a very typical case where the relationship between the input.

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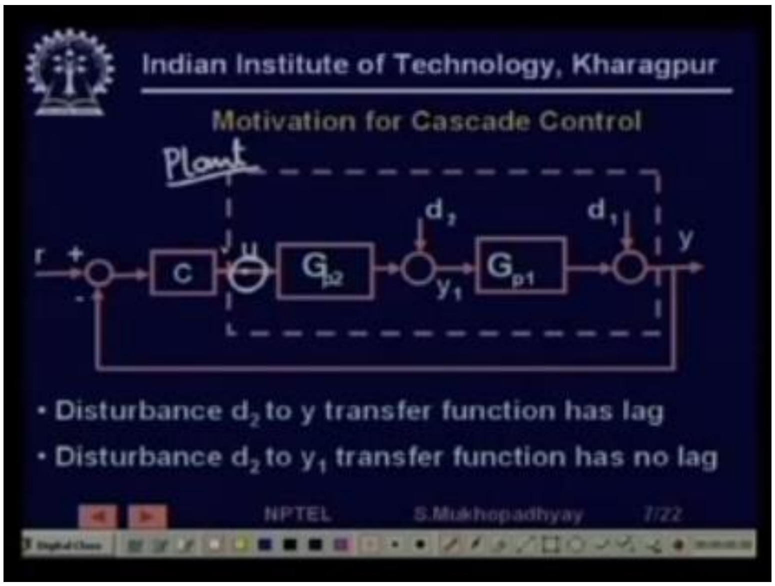

You know typically reactors are cooled using coolant liquids which flow through jackets of the reactor, so the reactor has some space in its wall and you circulate coolant through that space so that you can cool the temperature of the reactor this happens for exothermic reactors where the reaction itself produces heat.

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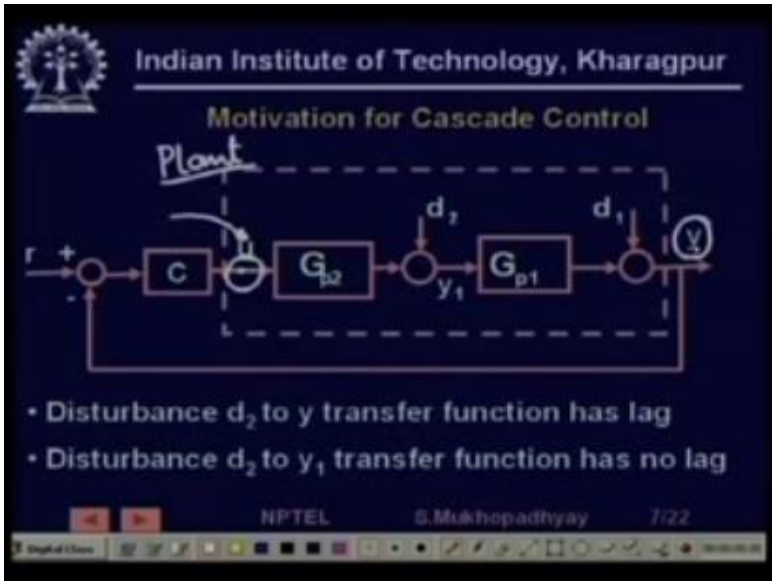

So the input is the steam flow rate and the output is the temperature of the reactor which you want to control, so between so how does these steam flow rate translate into a temperature so there are various stages so for example first if you put not just steam flow rate coolant flow rate so first the coolant flow rate will establish a temperature in the jacket then because there will be temperature difference between the tape between the jacket and the reactor interior.

So there will be heat transfer and heat will come from the reactor to the jacket and therefore the temperature will fill fall, so there are basically two different mechanisms one is from flow to establishment of temperature in the jacket and from jacket to affecting the that is from the jacket between the jacket and the reactor heat transfer mechanism.

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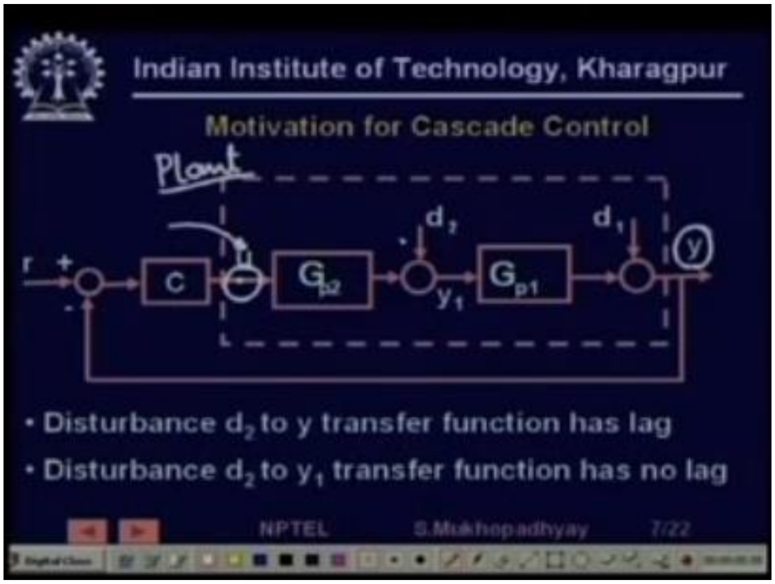

So they are so such things happen and you have for example in a motor in a motor suppose you want to control position. So you give what you give you give you change the electrical voltage at the terminal of the motor so the voltage relay suppose it is a DC motor so basically you change the armature current if you change the armature current then what you change is torque so basically the input that you are giving is torque.

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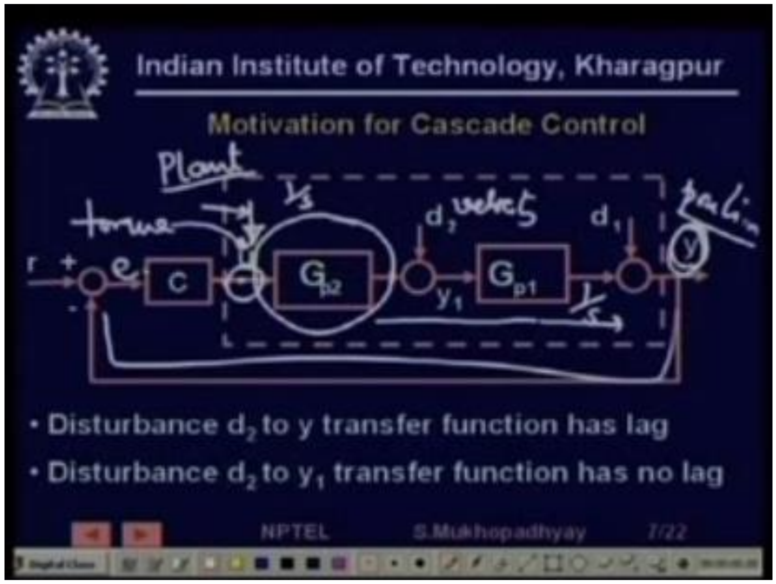

Now and the so here you have torque and here you have position suppose a position control application, so between and so from torque is directly proportional to acceleration just divide moment of inertia you will get acceleration, so that is constant but between acceleration and velocity there is one integration so this could be integration 1/s and here you have velocity again between velocity and position you have another integration.

So this is another 1/s and you get velocity and you get position, so you see that the between input torque and output position you have two different subsystems in this case in the case of a motor it is an integral. So this is a very typical situation now in this situation there can be you know there can be disturbances everywhere for example there can be load disturbances so and where does the load disturbance come.

The load disturbance can come in come in various places it can in this case in the case of the motor it can come it can come at the input itself because total electromagnetic torque minus load torque will give you the net torque, so if a load disturbance comes here this must traverse through this whole process and then it will affect the output and then it will be feedback and then there will be error. So it takes a lot of delay this is the reason why.

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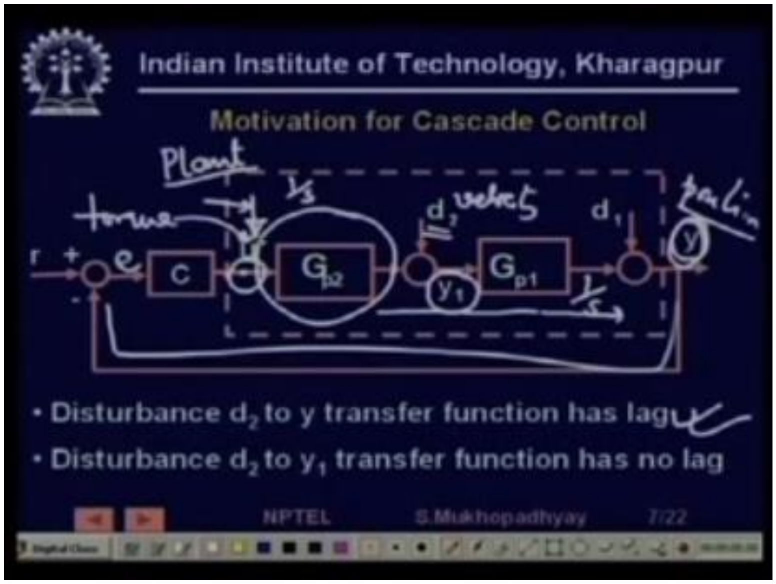

So what happens is that if you have so much of phase lag then what sometimes what can happen is that you see the stability margins are lower so disturbance d2 to Y transfer function has lag and the but it so happens that this intermediate variable Y1 is immediately affected by D 2 in this case or even if the disturbance is acting here the transfer function between the disturbance here and the measurement and the and the and the variable y1 has much less lag.

Than the transfer function than the lag between this disturbance and this output, so now this is this an observation so here is an intermediate variable.

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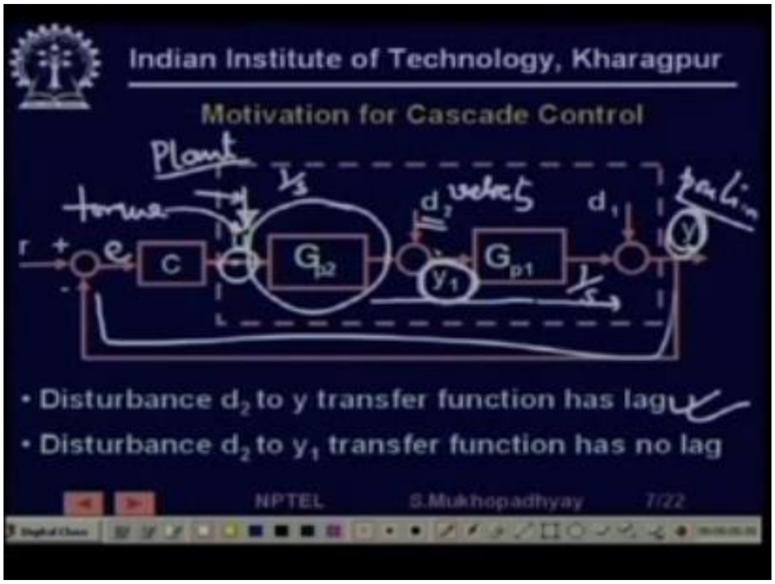

Which we are not using maybe it could be measured maybe it could be measured very simply for example in the case of the cooling reactor suppose we could measure the jacket temperature why not that that involves simply putting a putting a temperature sensor similarly most position control loops have speed feedback so putting so measuring the shaft field requires simply putting some kind of a tachometer or speed encoder. They are not very difficult to measure the advantage is that now we have another measurement.

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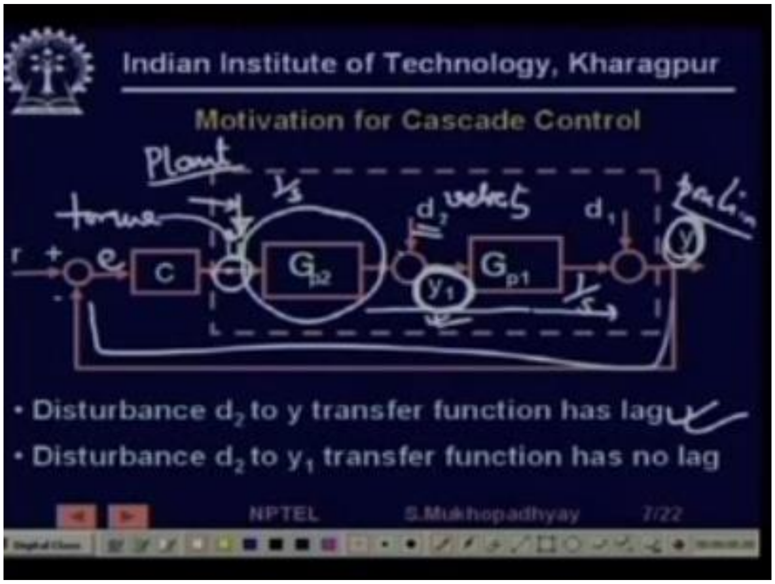

So you see that so if the question is that if we could measure some intermediate variable Y1 then feeding it back does it give any advantage actually it gives plenty of advantage you can give significant improvement in response to disturbance also improvement intransient response to step 2 set point changes because the controller again can be significantly enhanced.

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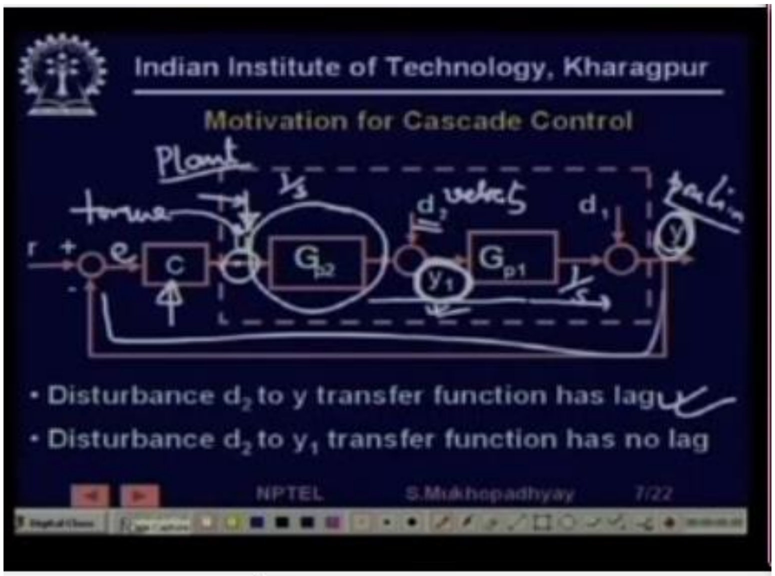

So that is achieved by cascade control, so how? Let us see that. So we look at cascade control, okay.

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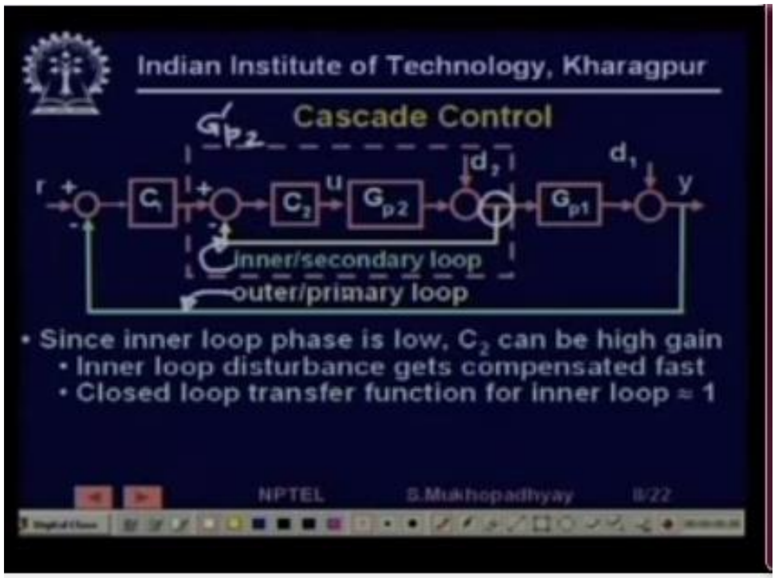

So now what are we doing, so let us look at this first of all suppose we have decided that there is some intermediate variable there is some intermediate variable Y1 which I am going to measure and I am going to feed it back so you see that now the Y feedback loop this is the outer or primary loop which is the standard loop, in addition to that inside the loop we have put another loop which we call the inner or the secondary loop.

Now what is that what is the function of the secondary loop, there are several interesting function firstly if you look at it from the primary loop point of view so now previously it was in the loop there was C1, gp2 and gp1, now we you have in place of GP2 you have GP'2 which is the closed-loop transfer function of this inner loop, previously you had only this gp2. So what is the difference between G'P2 and GP2?

Firstly G'P2 has much less phase much less phase lag that is that is always true because of the fact that closed loop systems have much less phase lag than open loop systems.

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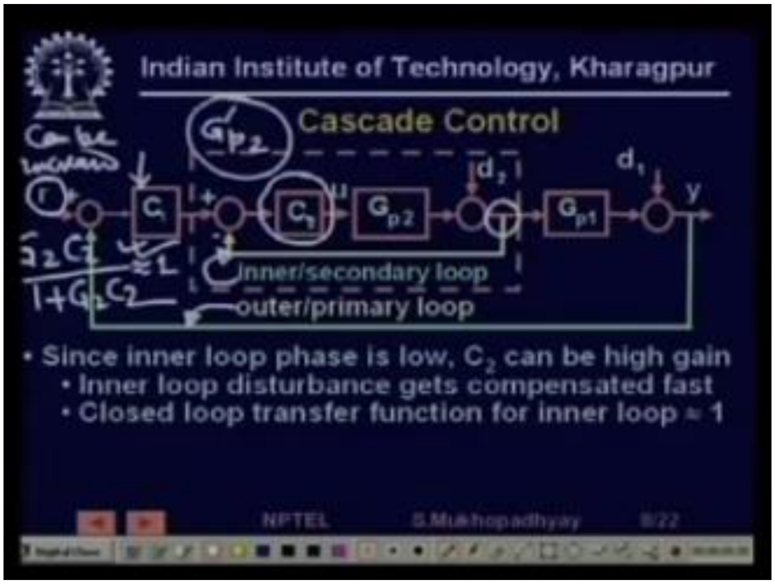

So this has much less phase lag which means that if you look at it from an outer loop point of view this C1, G'P2, GP1 combination the overall phase lag has now reduced. So if it has reduced then the value of C1 which can be increased this value of the gains of the controller can be increased, right. So c2 can write, now which means that overall transient response will increase because now r any set point change in r will be acted upon much faster by c.

Because it has higher gains. So that is a very good advantage, so which means that we must design this loop such that this G dash V 2 has significantly lower phase. So when can we do that, so when does a closed loop system have low phase where c2 is high you see closed loop transfer function is what, it is G2, C2, G2, C2/1 + G2 C 2 is the closed loop transfer function of the inner loop.

So if C2 is can be made high then this becomes almost equal to 1 so the phase loop, phase lag reduces to 0. So we should be able to use a high C2 but can we use a high C2, yes we can because as far as this loop is concerned this loop phase lag is only GP2. Previously the outer loop we are having problem because the phase lags of GP2 and GP1 were actually adding up, but now in the inner loop we have only the phase lag of GP2 to take care of.

For example, as far as our motor control is concerned GP2 has maximum has around 90˚ phase lag so if something has a 90˚ phase lag is a first order process then we can theoretically speaking, we can use very high gains of C2. And if we use very high gains of C2 then this closed loop transfer function will be almost equal to 1. So it is indeed possible to head for C2 to have to be. So since inner loop phase is low much lower it may be, it is often possible that C2 can be very high gain.

And then the outer loop phase is also reduced significantly and therefore C1 can be a of Eigen, so that is the point second thing is that previously we were thinking that this response of d_2 travels to y much slower so taking care of d_2 takes time now what happens is that the effect ofd_2 or even the effect of let us say if we have some disturbance here like in the case of a motor the time it takes from here to here is much lower than that from here to here.

Similarly from here to here is from d_2 to the here is immediate and since this loop has very high gain so therefore this defect of either disturbance either here or here gets very quickly corrected in the inner loop itself and it does not travel to the outer loop, so we have been able to contain the disturbance within the inner loop and we are not yes we are we are able to stop it from spilling over to the outer loop so the effects of inner loop disturbances are neutralized very fast in the inner loop these are very significant advantages and as is said here so the outer loop phase is low.

So C_1 can be high gain and better transient response for the overall system so you see that you have several advantages you have better stability margins you have you can contain inner loop disturbances within the inner loop and they will not affect the output they will get connected in the inner loop and thirdly speaking your overall transient response will improve because you can use higher gains in the outer loop right and all this you are getting at the expense of an additional measurement number one and number two are slightly more complicated control law. So these are often very low prices to pay for a better control of the process.

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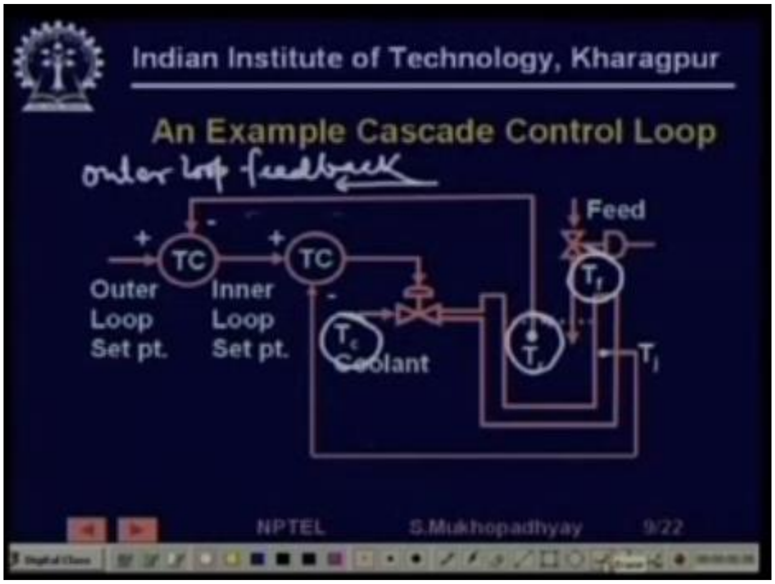

Therefore they are very widely used we will look at an example a practical example so what we are having here is that we are having we want to control this is that this is a kind of an exothermic reactor so we want to control the temperature of this reactor this is what we want to control so obviously we are giving a feedback here this is outer loop so this is the this is the outer loop feedback or primary loop feedback.

So initially let us assume that this is not there so you see we could we could we could actually do away with this and actually use in one single loop control we could remove these parts this feedback is not there we could use that and we can have a normal control loop so what are the disturbances the disturbances are there could be several disturbances for example there could be a feed temperature T_f which will cause temperature of $_{Tr}2$ temperature of the reactor to change this is a disturbance which will get quickly effect T_r there could this there could also be a disturbance in the coolant temperature the coolant itself you are controlling the flow rate of the coolant but the temperature of the coolant is not known probably that is not in our hand.

So the temperature of the coolant itself could act of the disturbance and this will take a lot of time to travel to T_r because first of all this has to change this temperature coolant will have to change the temperature of the whole jacket that itself is the heat transfer and mixing process once that jacket temperature is changed then through another heat transfer process the reactor temperature will change and then only feedback will go and then only the flow rate will get affected.

So now instead of that if we use instead of that if we use so now we are going to use the use of cascade control loop so we have made another measurement one moment please want to take care of the eraser oh okay I got it yeah so what we have is instead of that.

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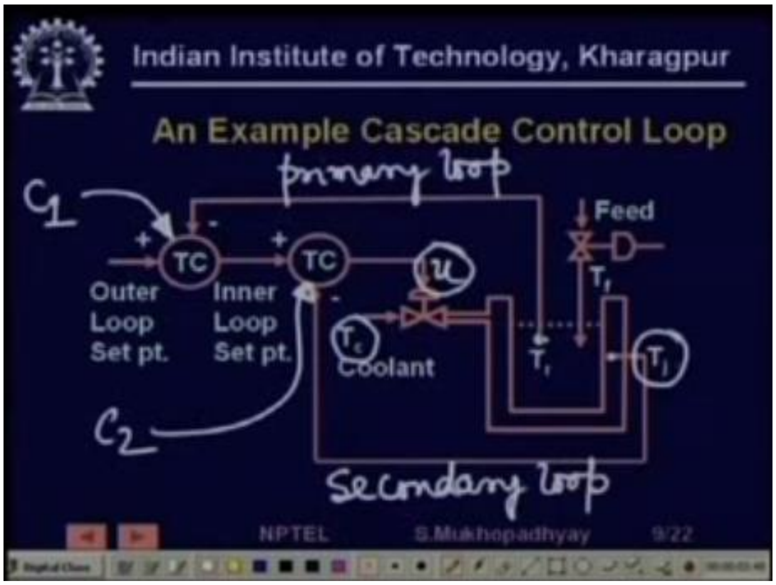

We have a cascade control loop where we are now incorporating this additional measurement called the jacket temperature and we are feeding it back right so this is our this is my secondary loop or inner loop and this is my primary loop so now what I am doing is I am giving so this so the primary loop feedback is there that is error it is coming to the first controller so this is my C_1 and this is another temperature controller which controls the jacket temperature that is my C_2 and finally this is my u now what happens is that if there is a coolant temperature change then that will affect T_J much faster and it will get feedback.

And therefore the flow rate will automatically get changed very quickly even before that it can start affecting the reactor temperature so this is a so here is a here in fact I mean such temperature control loops in chemical processes are almost without exception there they are cascaded just like in motor position control loops you always have a even have a velocity feedback is very rare when you do not have cascade control.

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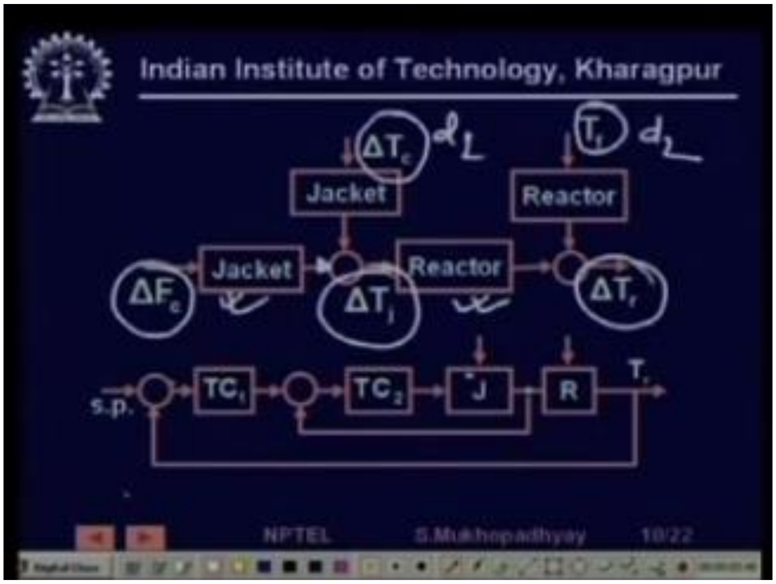

So we come to the so this is a this is this is at this is that I am trying to model that situation basically so it shows how things are so ΔFC which is a change in the flow of the coolant first in you so that excuse me so this just shows that this ΔFC affects this ΔTJ through the jacket. Similarly this ΔTC in fact actually these effects are this flow and temperature these effects actually multiplicative, so I have considered their increment so that they become additive. So this shows that this ΔTC also affects ΔTJ and then once ΔTJ is established then between ΔTJ and ΔTR there is a reactor heat transfer dynamics.

And similarly the feed temperature change also affects the reactor dynamic, so this is one disturbance d1 this is the other disturbance d2. And we are giving a feedback around this jacket and again another feedback around the reactor. So basically this is explaining that thing.

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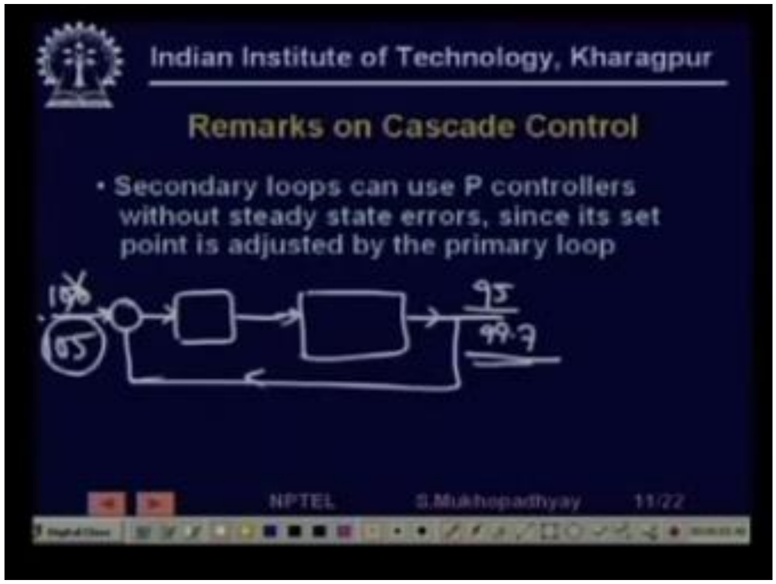

Then so this is having understood cascade control which see some remarks that important remarks is that firstly secondary loops can use P controllers, why we know that P controllers can result in steady state errors. So but it so happens that for example firstly the secondary loop output is not a real output, so even if there is a steady state error we are not going to, we are not interested as I mean per se to control that output.

Secondly we have already seen that if there is a steady state error what is the way of one way of going around it is by increasing the set point. So suppose in a control loop if you give hundred there is some steady state error because there is some proportional controller. And here you get say 95 you know that you get a steady state error in this loop. Then one way of getting around the this problem is that you rather than giving 100 you give 105, if you give 105 you will probably get something very, very close 99.7 or 8 or something you will get.

So the technique is that you adjust the set point, now for the inner loop who adjust the set point that the set point is adjusted by the outer loop. So interestingly the, if there is a steady state error then what will happen is that the outer loop will slowly adjust the set point to the inner loop and the steady-state error will vanish. So therefore, you can use P controllers.

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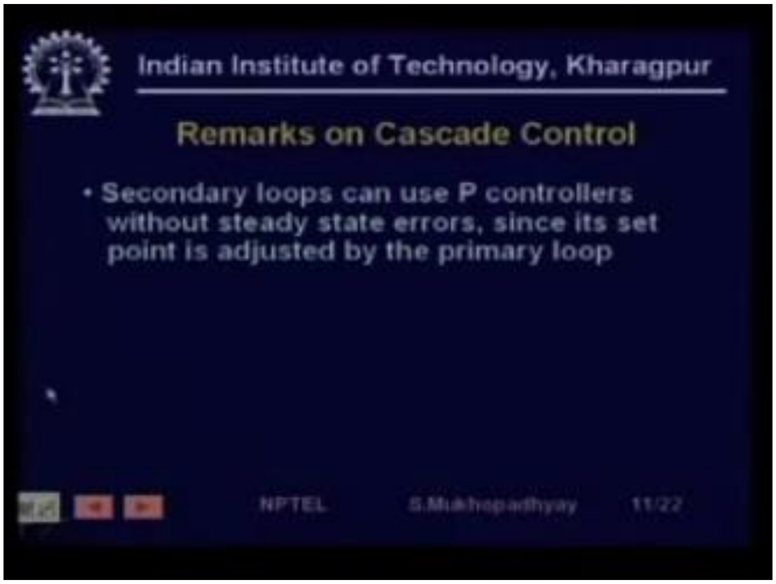

The second typically flow control loops are often secondary loops, and there is also a significant advantage because this flow control devices called valves or sometimes very significantly nonlinear. So something is a nonlinear means what, see all the time we have various nonlinear systems and we are looking at them, we are we are trying to analyze them using linear control theory.

So which means that we are using, you know their incremental characteristic that is we are taking locals loops and then we are considering local slopes in the characteristic and we are considering them as the gains. So the valve incremental gain changes considerably depending on in which region of flow you are operating. So now and remember that you have lag so you want to keep the overall process gain lower.

So and this process gain keeps varying because the fouls gain keeps varying, so what do I mean how do you design a controller. So to design a controller you will have to keep the, you have to make a conservative estimate of the controller gain, so that even for the highest valve gain it will not go unstable right. But what happens here is that since the valve is in the inner loop so the inner loop controller imagine what is the job of closed loop control, see the job of closed loop control is such that even if there is a variation in the process gain the closed-loop transfer function is not affected.

So the closed loops of the valve variations are actually taken care of in the inner loop and in the outer loop you can design a, so the inner loop characteristic, closed loop characteristic is there is much less because of valve gain variations and you can, you are able to make a much better estimate of the controller gain. So this is another advantage of cascade control.

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But for cascade control to be effective we must remember that this overall phase lag must be well distributed over this GP1 and GP2 because suppose, that GP1 is a constant key, there is no phase lag and all the phase lag is in GP2. Then what happens, then what is the idea of giving a feedback here, see then the feedback of the open-loop plant loop gain of the open-loop plant, loop phase are same, because both are constants.

So therefore, the problem of loop phase still remains and the whole problem will come in the outer loop. So it is becoming like the old case, similarly if you put, similarly if you put this one as K, and this one as GP1 and put all the phase lag here then the problem will be to decide the inner loop. So the inner loop controller will now have the same stability problems as the overall process.

So in fact situations cascade control does not work well or in other words this, so what do you do so you have to choose a variable so the variable that we choose to feedback in cascade control should be very judiciously chosen, it should be chosen such that it divides the plant into two sub processes of balanced phases right, then the cascade control loop will actually work well.

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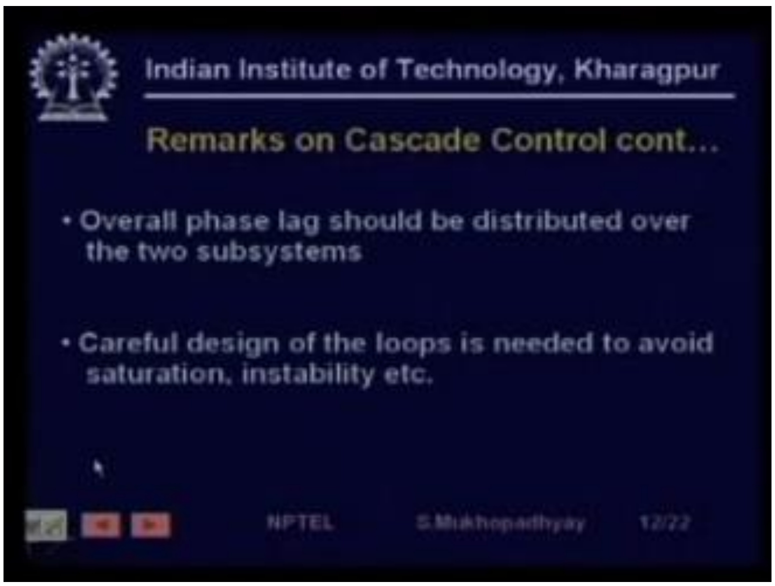

So and well there are several other issues which we are not going to consider here, but there may be for example, there may be issues of saturation of actuators, there will be issues of you know frequency detuning of the inner loop and the outer loop that is when the overall gain will peak at some frequency in the closed loop, in the inner loop and some other frequency in the outer loop. So such are there they are more complicated issues of design and we need not look at them at this stage.