Advanced Control Systems
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Module No. #01

Model Based Controller Design

Lecture No. #02

Control Structures and Performance Measures

In today's lecture, we shall discuss about some control structures. We shall see how placing the controller in different locations will result in better closed loop control systems. Before that let us come to the simple fan speed control systems to learn something more about a closed loop control system.

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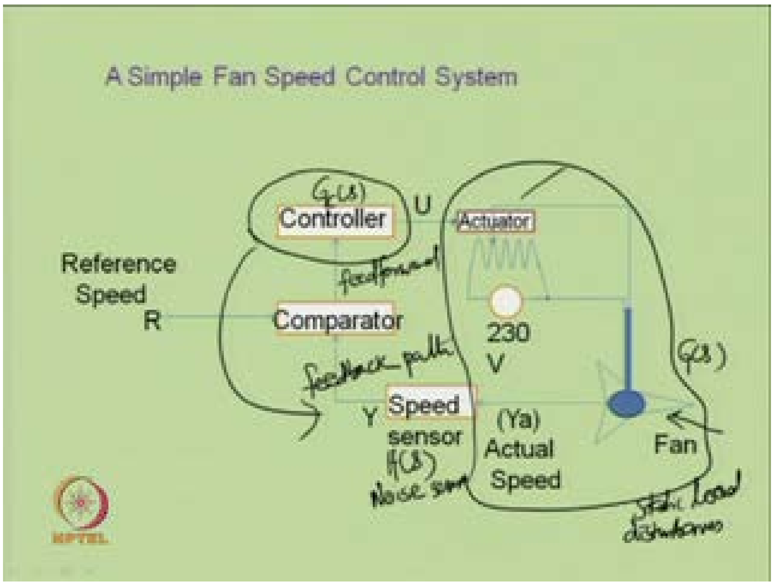

Here in the simple fan speed control systems, we have included one actuator; the job of actuator is to effect changes in the plant dynamics based on the controller input. Now, we shall represent the controller dynamics by G c (s) and actuator plus plant dynamics by G (s), and sensor dynamics by H (s) in our subsequent lectures. Now, lot of things has to learn from a complete closed loop control system. When the fan is running, it might be subjected to some disturbances like, when the ventilator of a room is opened, that time we might get some actions affecting the fan dynamics. Those will be known as static load disturbances, static load disturbances.

Similarly, in the case of inaccurate sensors, we might get noise in the sensor. Those are known as sensor noise; due to imperfection or drift in the components used in a sensor. Most importantly an user has freedom to place the controller anywhere in the loop, in the closed loop controller control system. The controller can be in the feed forward part, feed forward part, whereas it can be located in the feedback path as well. Now a control system has got a feed forward path, a feedback path, and the actuator in the loop. Now, depending on the location of controller, one may get varieties of control structures. What are those control structures, we shall see in the subsequent slides.

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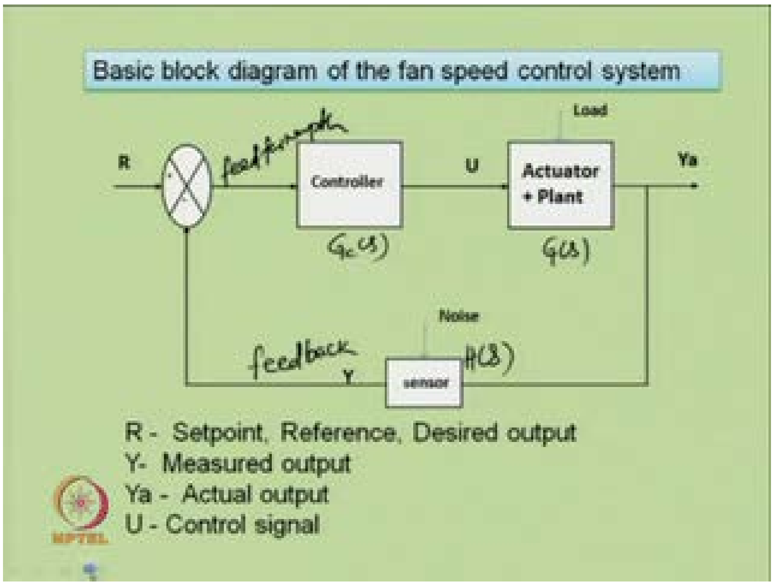

This gives the block diagram representation of the fan speed control system; where actuator and plant dynamics are put together giving us G (s); controller dynamics will be shown by G c (s), and sensor dynamics by H (s). In this scheme, as we have discussed earlier, the controller can be put even in the feedback path, giving us other type of control structure; we have got the feed forward path here. Now, in the block diagram, the controller is put in the feed forward path. Is it sufficient for representing the closed loop system in this fashion? No. We have got different type of structures and one such structure can be shown by this figure.

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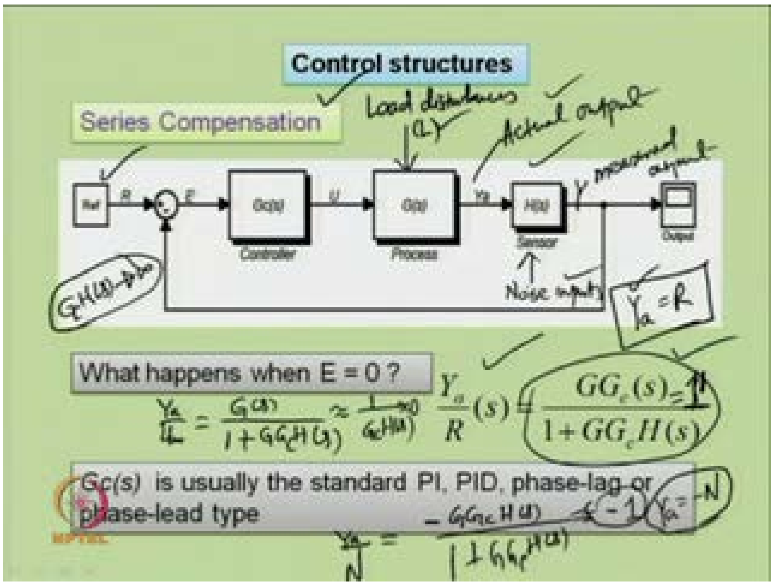

This block diagram represents a series compensation scheme, where the controller is in the feed forward path, along with the process; sensor is also put in the feed forward path in this fashion. Y a is the actual output actual output, whereas Y here is the measured output, measured output. So, we have to keep in mind, there is a sensor in between the measured output and the actual output. This type of series compensation is found to be used extensively in processing the stretch, particularly for set point tracking. What else trackings are there? Objective can be to reject disturbances in a closed loop control system; such types of systems are often known as regulatory control systems or regulatory systems.

The prime objective of series compensation scheme is to find a device one perfect set point tracking system. Now, in the series compensation scheme, the process might be subjected to load disturbances; similarly the sensor might be subjected to noise inputs. What happens when E equal to 0? This is a big question, because very often I have found in the class that students are unable to make out given a series compensation scheme; what happens when E equal to 0? If I look at the block diagram, when E equal to 0, then u is expected to be 0, and the process does not get any sort of input, then we may not get any actual output from the system; that is not the case; to explain that, we may have to go to the first slide, to make the things clear.

When this E equal to 0, we have got E equal to 0 is the difference between the reference in speed and the measured speed. When E equal to 0, controller output might be zero; but at that time, the fan is not restricted from the input supplied. That way the fan rotates, E becomes 0, when the difference between the actual speed and the reference speed is zero; that means the fan has achieved the desired speed. When the fan has achieved the desired speed at that time, the controls controller may not act, controller action is redundant; one do not require controller in the loop, when we are getting the desired speed from the fan. But the input to the fan is not disrupted; rather the control signal equal to 0 therefore, the actuator may not be acting; whereas the fan is in action and giving us the desired speed. So, when E equal to 0, still the process go on working; the still the processes go on working.

Now, next coming to the closed loop transfer function, we often get from series compensation schemes are given by G G c (s) 1 plus G G c H (s). How do we get that transfer function? If I look at the series compensation scheme and make use of either block diagram reduction technique or signal flow graph analysis; it is very easy to get the closed loop transfer function in that specified form. Let us derive the way one can obtain the closed loop transfer function.

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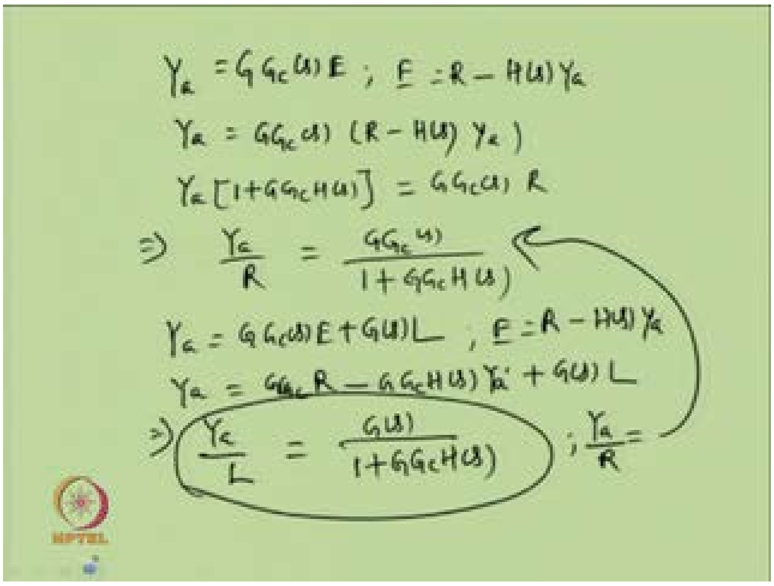

Y a can be written as GG c (s) E. Well E will be equal to R minus H (s) Y a; thus giving Y a equal to GG c (s) R minus H (s) Y H (s) H (s) Y a; upon simplification, we get Y a 1 plus GG c H (s) equal to G G c (s) R implies Y a upon R equal to GG c (s) upon 1 plus GG c H (s). This is what we have got in the previous slide. Similarly, if one takes into account, the load disturbances designated by L, the output with respect to L can be obtained using super position principle. In that case, Y a can be made up of Y a equal to G (s) times l plus u G s times l plus u. Now that can be written as Y a equal to GG c (s) E plus G (s) L, where E is as given earlier R minus H (s) Y a; giving us Y a equal to GG c R minus GG c H (s) Y a plus G (s) L; giving Y a upon L equal to G (s) upon L plus GG c H (s).

We have already found, if the transfer function Y a upon R as given above. So, we see that Y a upon L, the impact of static load disturbance upon the actual output can be given by the expression Y a upon L equal to G (s) upon 1 plus GG c H (s). Similarly, I can find the impact of effect of noise inputs on the actual output Y a; and that expression can easily be obtained as Y a upon n equal to minus GG c H (s) upon 1 plus GG c H (s). Now, why are we we finding all these transfer functions, to see the effect of different type of inputs on the process output. The process output is made up of three outputs; one is given by the reference input, the load disturbance input and the noise input.

Now, how the controller is designed to have a perfect tracking system from this series compensation scheme? Often it is desired to design a controller such that this G c H (s) tends to infinity; it is very high. When G c H (s) is a very large number, then this can be approximated to 1 upon G c H (s). This can be approximated to 1, and this can be approximated to minus 1. So, we have got a perfect tracking system with the use of the controller G c (s) with proper design of controller G c (s), when the controller gain is assumed to have very high value; at that time, Y a upon R s becomes 1; that means, Y a becomes R, which is desired; that means, the actual output of the system becomes the desired output or the reference input.

Now, look at the impact of load disturbance on the measured output. Since G c H (s) is a large number, Y a L tends to 0; that means, the effects of load disturbances can be neglected, can be nullified, can be overcome with the use of large gain of the controllers. But one thing one has to make out, if you look at carefully this one, the noise is not getting suppressed; Y a is becoming minus n. So, the noise is not getting suppressed with the high gain of the controller. So, some trade off up has to be made to design proper controller, such that not only the set point tracking is made proper tracking system is designed, but also all the disturbances are suppressed as much as possible; that is the design that is the design objective of a closed loop control system. So, this is the series compensation system coming under control one of the control structures. We have many more control structures; the controller is put at various locations in the closed loop to get desired output from the system or to meet the design specifications of a control system.

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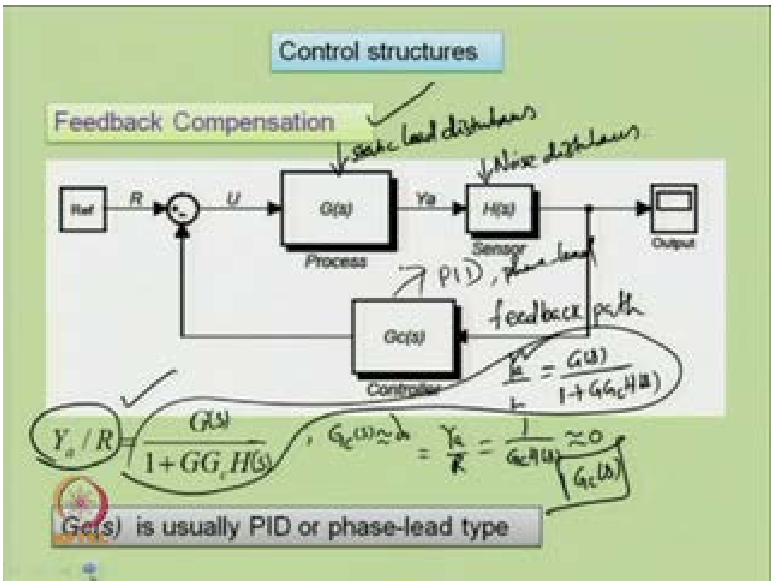

Let us see another type of compensation scheme, often known as feedback compensation scheme. Now feedback compensation schemes are used for closed loop systems, where regulatory response or disturbance rejection is the main objective. These types of systems, compensation scheme are expected to give us proper regulatory systems. What do we mean by a regulatory system? A regulatory system means, where the output will reject the disturbances, external disturbances only it need not go on tracking the reference inputs repetitively. Consider the case of a voltage regulator; often we desire to have 230 volt output from a voltage regulator. In spite of the input voltage fluctuations, the output from the regulator is expected to be 230 volt. Thus that gives us a voltage regulator. For such type of control systems, often feedback compensations are found to be useful.

Now, in the feedback compensation scheme, the controller is in the feedback path. Thus giving the closed loop transfer function Y a upon R as G (s) upon 1 plus G G c H (s). Earlier for the series compensation scheme, we had got GG c in the numerator, whereas for this scheme, we have got G (s) alone. So, when the controller gain is very high G c (s) is assumed to be very large; in that case, Y a upon R becomes 1 upon G c H (s); and that becomes a small number. Thus the feedback compensation scheme is assumed expected to have least disturbances, the output is expected to have very less effects of disturbances, external disturbances; what do we have the disturbances? The controller may not introduce any disturbance, the process might be subjected to static load disturbances, and the sensor is subjected to noise disturbances.

Now, using the principle of super position, again it is not difficult to find the transfer function Y a upon L, which can again be given in the form of G (s) upon 1 plus G G c H (s). If you look at carefully, the transfer function with respect to the reference input, and the transfer function with respect to the static load disturbance input are same. Thus facilitating one to design a controller conveniently, because the two closed loop transfer functions are equal, so same technique or same criteria may be used to design the controller G c (s) whereas, for series feedback compensation scheme that is not the case. Now, what type of controllers are often used in the feedback compensation scheme G c (s), the controller is found to be of PID type or some phase lead type; it is often found to be of phase lead type. What are those PID type or phase lead type of controllers? We can find their transfer function form.

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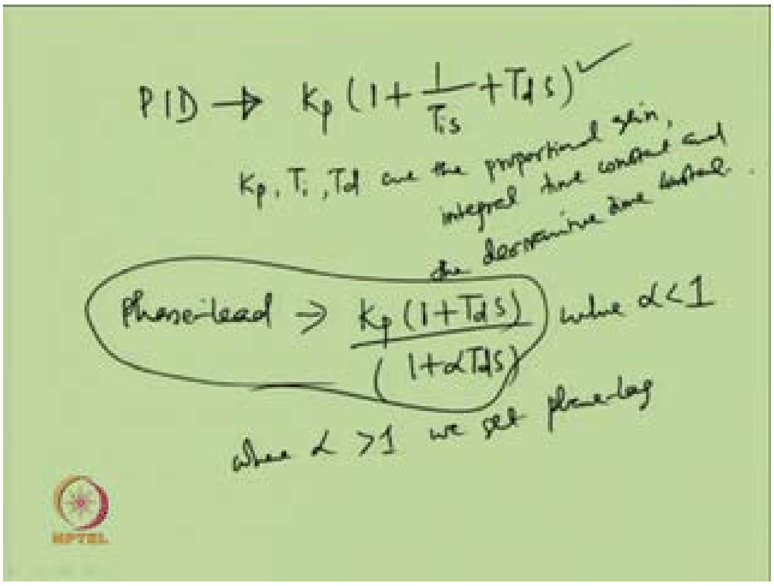

A PID controller can be is shown in the transfer function form as K p 1 plus 1 T i s plus T d S, where K p, T i and T d are the proportional gain, integral time constant and the derivative time constant of the controller. So, this form of transfer function is often known as also parallel form of PID controller transfer function. What are those phase lead type of controller? Phase lead controller transfer function can be given by some K p 1 plus T d S 1 plus alpha T d S, where alpha is less than 1. When alpha is greater than 1, we get phase lag action from the controller. So, this gives us the transfer function of a phase lead controller. Let us see other type of control structures that we might have in many practical control systems. One such control structure is often known as series feedback compensation scheme, which combines the effects and advantages of both series and feedback compensation schemes.

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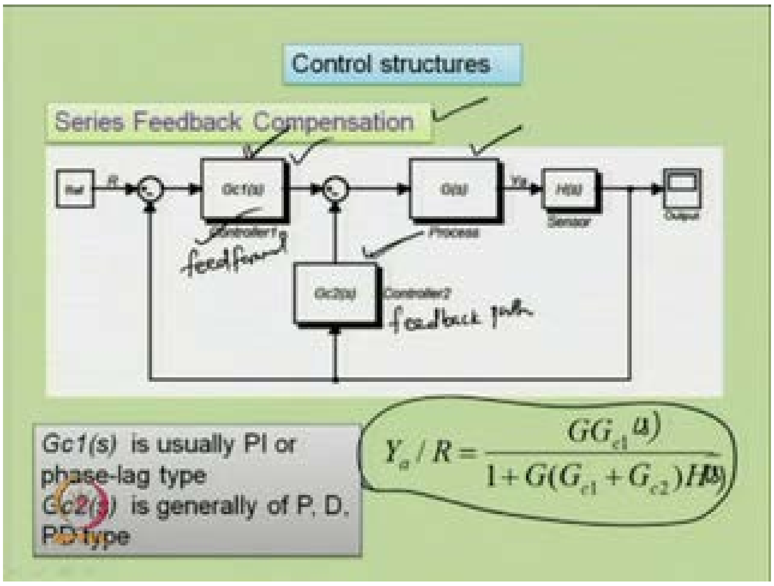

Here, we have got the controller 1 in the feed forward path and controller 2 in the feedback path. With the help of this control or compensation scheme, it is possible to obtain satisfactory set point tracking and a disturbance rejection, both; that is why it is often also called a two degree of freedom control scheme. Now, G c 1 is usually a pI or phase lag type of control, and G c 2 is generally proportional derivative or proportional derivative type of controller. The closed loop transfer function with respect to the reference input can be given by this expression GG c 1 (s) 1 upon plus GG c 1 plus G c 2 combined H (s). How it is different from the series or feedback compensation schemes?

When we said G c 2 equal to 0, we get a series compensation scheme; when G c 1 is said to 0, then we get the feedback compensation scheme.

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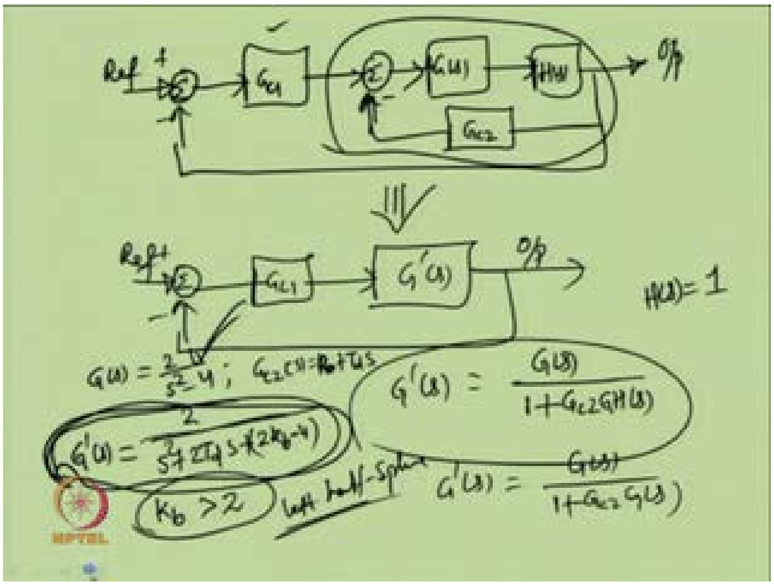

Now, often with the help of block diagram reduction, this series feedback compensation scheme can be shown in the form of reference input comparator, then we have got the main controller G c 1 or the controller in the feed forward path G c 1, and we have got the process including the actuator dynamics G (s), sensor dynamics H (s), and output. Now, I can redraw it in this form; putting the controller G c 2 feedback controller in the inner feedback path. Why this is arranged in this fashion? So that to make out that, G c 1 is primarily going to control a modified process. How that is possible or how that is evident from this block diagram? Let us redraw its equivalent representation; where we will have G c 1, and then we will have G dash (s), output; where G dash (s) can be given as G (s) upon 1 plus G c 2 H (s).

So, basically we are getting a series compensation scheme with a modified process dynamics. What is this G c dash (s)? G c dash s is G s 1 plus G c 2 H (s). So, assuming the dynamics of the sensor to be 1; H s to be 1; we get G dash (s) as G (s) upon 1 plus G c 2 G (s) sorry we should have G c 2 G H (s) over here. Now, how that is advantageous? This inner feedback enables us to place the poles of the original process at certain desired locations. To supplement that to support that, let us consider a plant transfer function G (s) is 2 upon S square minus 4; and the controller G c 2 a PID controller of the form of K b plus T d S; then that will give us the inner loop as G dash (s) equal to finally, 2 upon S square plus 2 T d S plus 2 K b minus 4.

Look at this closed loop transfer function, inner closed loop transfer function; when K b is greater than 2, we get a stable transfer function G dash (s) will have poles, which are located in the left half of the S plane. So, with proper design of the control parameter K b; that means, when K b is greater than 2, it is possible to locate the poles of the original on stable process G (s), which has got one pole in the right half S plane having both its poles located in the left half S plane. So, the original process as a pole in the right half S plane; now the revised process or the modified process G dash has got both its poles located in the left half S plane. Thus giving us some modified process convenient to control. That is the benefit, we get the from the series feedback compensation schemes.

And next the controller G c 1 is designed for overall improved performance of the closed loop control system. So, the primary job of G c 2 (s), the inner controller is to position, place the poles of the process at certain suitable locations in the S plane; and then the G c 1 (s) takes care of the overall performance of the series feedback compensation scheme. So, that is the beauty of this series feedback compensation scheme, which combines the benefits of series and feedback compensation schemes.

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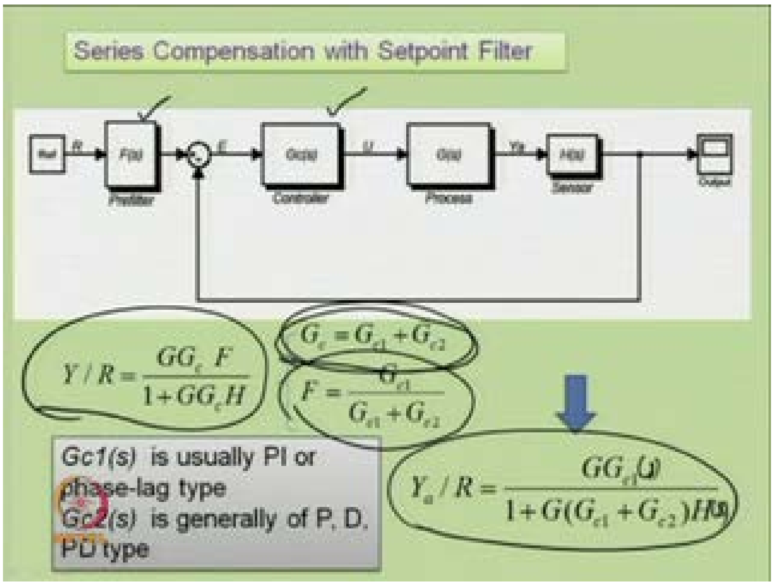

Now, we shall see any other type of compensation schemes we have; yes, we have got series compensation with set point filter. Here, we have got a controller in the feed forward path, one more pre filter also before the reference input in the feed forward path. How it is different from the series feedback compensation scheme? It is exactly same as the series series feedback compensation scheme, when the controller G c equal to G c 1 plus G c 2, and F equal to G c 1 G c 1 plus G c 2. So, if we put in the earlier structure, in the series feedback control structures, G c and F or if I put the earlier design G c 1 and G c 2 in this series compensation with set point filter, in this particular fashion G c equal to G c 1 plus G c 2, F equal to G c 1 G c 1 plus G c 2, then the closed loop transfer function from this scheme becomes GG c 1 upon 1 plus G times G c 1 plus G c 2 H (s) that is exactly what we have got from the series feedback compensation scheme.

So, this compensation scheme or control structure is not different from the series feedback compensation schemes; rather it has been redrawn in this typical fashion. Now, G c 1 is usually PI or phase-lag type, and G c 2 is generally of proportional derivative or proportional derivative type as we have used in the earlier series feedback compensation scheme.

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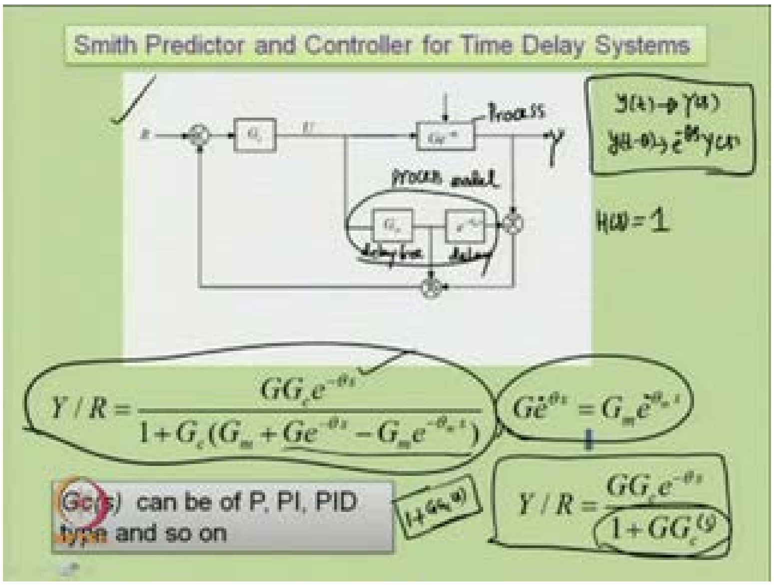

Now, we shall look at other type of control structures; a smith predictor and controller structure for time delay systems. This is totally different from the earlier three types of compensation schemes; in the sense that G e to the power minus theta s represents the process actual process, whereas G m e to the power minus theta m s represents the process model. So, the process model is made up of two parts; one delay free part, this is the delay free part of the process model, and the time delay or dead time part of the process model.

The actual process put in this fashion along with this process model gives us a smith predictor and controller structure. Smith predictor controller structures are generally used for effective control of plants or processes with long dead time. What do you mean by dead time? Suppose the process output is y (t); in Laplace domain, we represent it by y(s); when the output is lagging by some time theta second that is often shown as e to the power minus theta s Y (s) in Laplace domain. So, here the process is possessing long dead time, and often it is difficult to design either series or feedback or series feedback type of compensation schemes without resorting to the smith predictor control scheme.

Here in this structure, we have assumed H (s) to be 1; unlike the earlier series, feedback and series feedback compensation schemes, this block diagram does not show H (s), and is it is assumed to be unity. This is true always sensor is assumed to be perfect or ideal one with gain 1; thus giving us this simple smith predictor and controller structure. Now, the closed loop transfer function of the system with respect to the reference input can be given by the equation GG c e to the power minus theta s upon 1 plus G c G m plus G e to the power minus theta s minus G m e to the power minus theta m s. When the process dynamics exactly matches with the process model dynamics or when the process model dynamics is exactly same as the process dynamics, which is given in mathematics as G e to the power minus theta s sorry 1 minus will come here, G e to the power minus theta s equal to G m e to the power minus theta m s, this term will become 0, and will get the closed loop transfer function in the form of GG c e to the power minus theta s upon 1 plus GG c (s).

Although the structure appears to be complex one, complicated one compared to the earlier compensation schemes, we have discussed; still the closed loop transfer function comes in a very simple part. If you look at the denominator polynomial or the denominator of the transfer function 1 plus GG c (s); based on the denominator, it is very easy to design a controller for the smith predictor and the controller scheme. Now, how do we get this one? Detail derivations can be easily obtained. Now, look at the signals Y output, control output, reference input.

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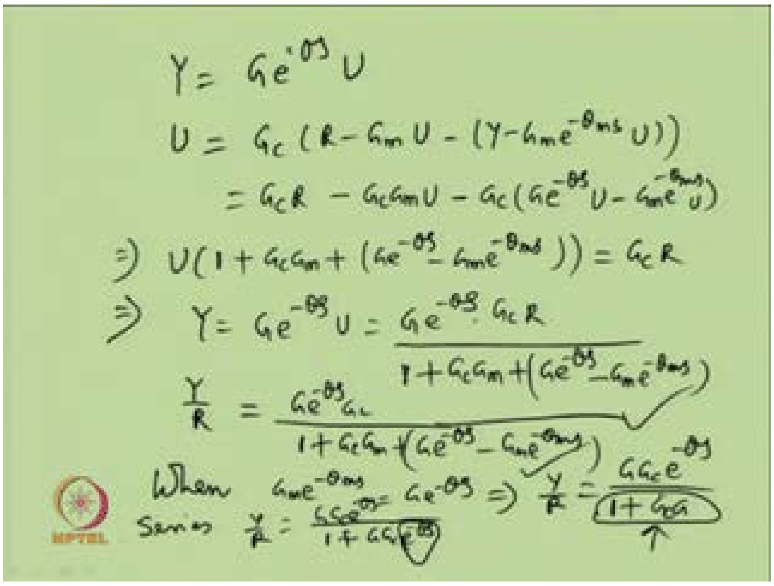

Using the information that Y equal to Y equal to G e to the power minus theta s U; again U equal to G c R minus G m U minus Y minus G m e to the power minus theta m s U equal to G c R minus G c G m U minus G c G e to the power minus theta s U minus G m e to the power minus theta m s U. Collecting the terms, one obtains U times 1 plus G c G m plus G e to the power minus theta s minus G m e to the power minus theta m s equal to G c R; thus giving us Y equal to G e to the power minus theta s U equal to G e to the power theta s times G c R upon 1 plus G c G m plus G e to the power minus theta s minus G m e to the power minus theta m s. So, we get the transfer function with respect to the reference input as G e to the power minus theta s G c upon 1 plus G c G m plus G e to the power minus theta s minus G m e to the power minus theta m s as we have seen earlier.

Now, when the plant model accurately matches with the dynamics of the actual plant; that means when G m e to the power minus theta m s equal to G e to the power minus theta s; Y upon R becomes G G c e to the power minus theta s upon 1 plus G c G or G m. So, this is the beauty of the smith predictor, the denominator of the closed loop transfer function with respect to the reference input is the void of any time delay term. Had there been the time delay term in the denominator? That we get from series feedback or series feedback compensation scheme, then it becomes difficult sometimes to design efficient controller for many systems. Now for the series feedback case, we get a transfer function of the form of Y R equal to GG c e to the power minus theta s 1 plus GG c e to the power minus theta s. So, this time delay term is not present in the closed loop transfer function of the smith predictor and controller. This is the added advantage of the smith predictor and controller that facilitates one to design controller conveniently.

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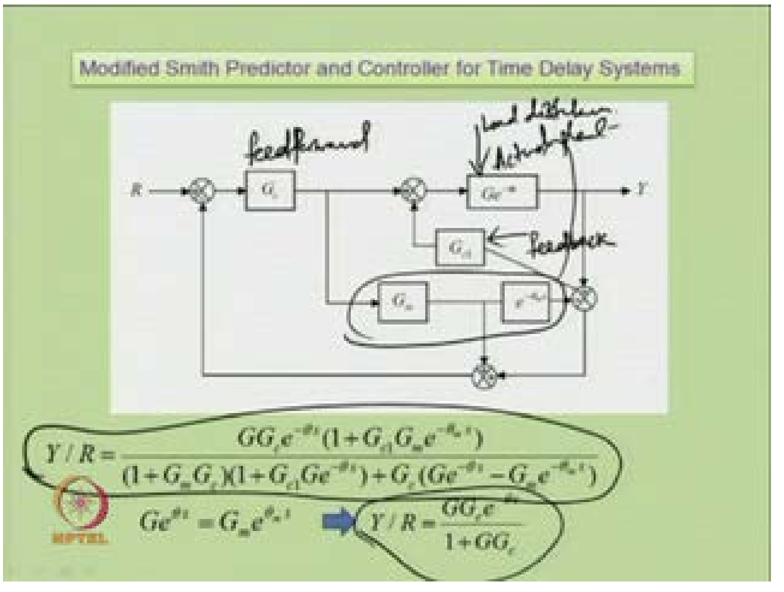

We shall see any other type of smith predictor controllers we have; over the years, many smith predictor and controller schemes have been evolved to take care of the deficiencies with the conventional smith predictor controller schemes. This control scheme introduces another controller apart from the main controller G c, which is in the feed forward path; we have got a feedback controller G c 1 in the feedback path. It gives a closed loop transfer function with respect to the reference input of this form. But when the plant model dynamics matches with the actual plant dynamics, then the closed loop transfer function becomes very easy; the one we have obtained from the earlier scheme.

But the benefit of introducing a controller in the feedback path is that it helps in reducing external disturbances, which is not the case with the earlier conventional smith predictor control scheme. So, when this process is subjected to static load disturbances, then the controller G c alone might not be sufficient to give us desired performance for the closed loop system, that is why there is the need for modifying the conventional smith predictor and controller scheme, to get advanced smith predictor controller scheme that can take care of external disturbances; load disturbances.

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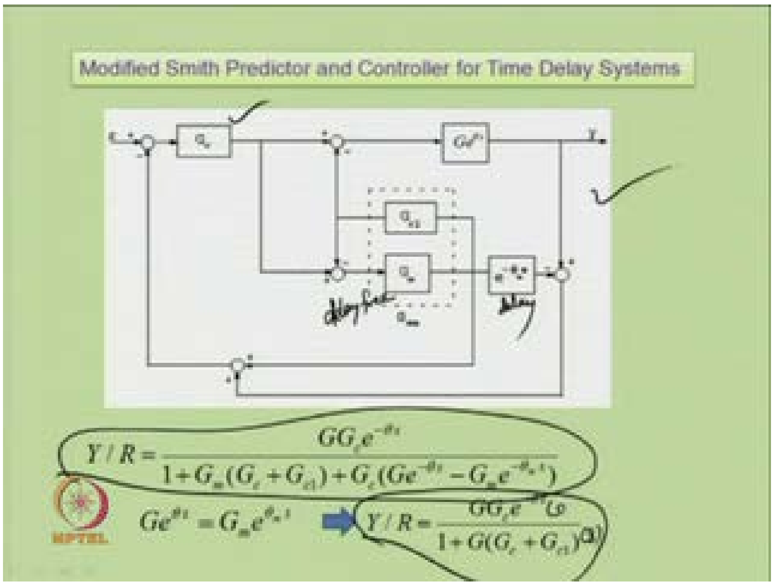

Apart from this modified smith predictor and controller scheme, we have got one more advanced modified smith predictor and controller scheme. It has also got two controllers; one controller in the feed forward path, and one in the feedback path. The second controller G c 1 (s) is across the delay free part of the process model, delay free part of the process model, whereas the benefit of putting the controller G c 1 in this fashion, you can make out, when you look at the closed loop transfer function with respect to the reference input. We get a closed loop transfer function of this form, and when we assume that the plant model dynamics accurately matches with the plant dynamics; at that time the closed loop transfer function becomes Y upon R as equal to GG c e to the power minus theta s as 1 plus G G c plus G c 1 (s).

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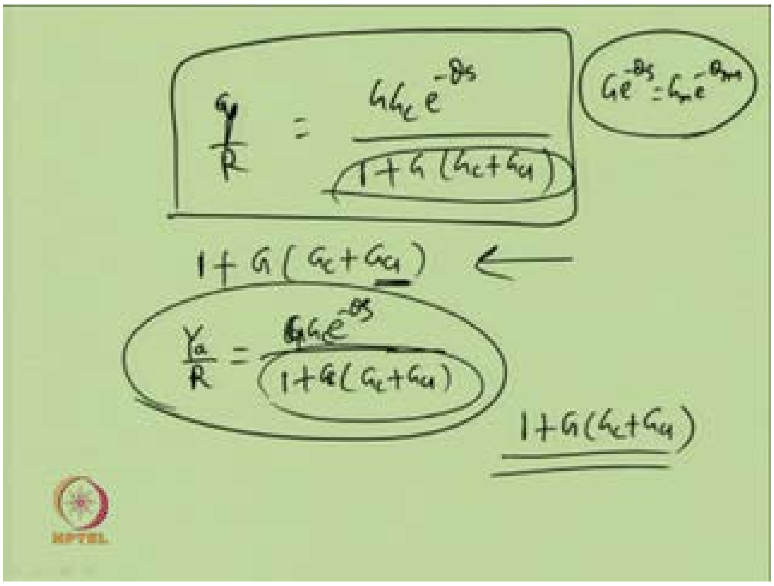

This closed loop transfer function shows us shows us that Y upon R equal to GG c e to the power minus theta m s upon 1 plus GG c plus G c 1. This could be theta s as well; since we assume that G e to the power minus theta s is equal to G m e to the power minus theta m s. Now, what is the benefit we are getting from this modified control scheme, modified speed predictor control scheme? If I carefully look at the denominator of the closed loop transfer function, it has got the controllers G c and G c 1 present in the denominator, which were not there in the earlier modified smith predictor or the conventional smith predictor and controllers.

This G c 1 helps in placing the poles of the process at convenient locations, as we had seen in the series feedback compensation scheme. The way we get a closed loop transfer function for the series feedback compensation scheme given at Y a upon R equal to G G c 1 plus G G c plus G c 1; here also this is the one we had for the series feedback compensation scheme, where this G is when the this G has got time delay, we have got terms like G e to the power minus theta s over here. The denominator has time delay in it, thus making all life difficult to design controllers conveniently, but the modified smith predictor will not have the time delay term, will not have the time delay term, thus giving us the denominator as 1 upon G G c plus G c 1. So, the benefits of a series feedback compensation schemes are also present in this modified smith predictor and controller structure.

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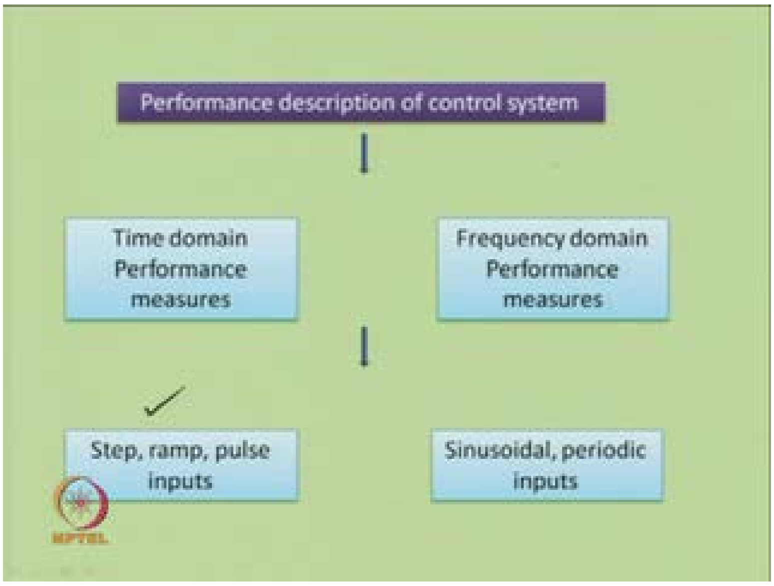

Now, we shall discuss performance description of control systems. Time domain performance measures of control systems can be observed easily from the time responses of systems. Similarly, the frequency domain performance measures may not be apparent directly from the frequency responses of a closed loop control system. Now, time domain performance measures are obtained with step, ramp or impulse inputs; whereas, frequency domain, performance measures are generally obtained with sinusoidal, periodic inputs to the closed loop systems. So, performance description of control system will be discussed in detail at length in our next lecture.

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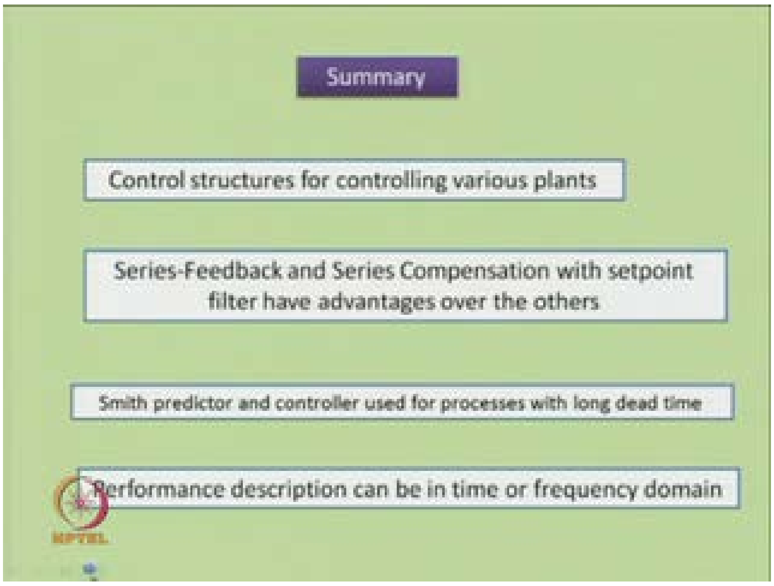

Let me conclude with this lecture. So, in summary, we have discussed varieties of control structures for controlling various type of processes; series feedback compensation scheme have got advantages over the series and feedback compensation schemes; smith predictor and controller are used for processes with long dead dead time. We have also discussed few modified smith predictor and control structures, which have got added advantages compared to the conventional smith predictor controllers. Performance description can be in time or frequency domain that we shall discuss in at length in our next lecture. That is all about the lecture.

Let us go to the question, answer session for this lecture. One may ask, what are set point tracking and regulatory control system? In set point tracking systems, the job of the control system is to accurately track the reference input; whereas in regulatory control systems, the job of the controller is to reject the external disturbances as far and as effectively as possible. Next question might be, are there any other control systems apart from the series feedback and smith predictor compensator control schemes? Yes, definitely, there are many control structures named as cascade control structures, internal model control structures and so on.

Third question would be why do we consider mainly unity feedback control systems? Actually, the job of a sensor is to carefully represent or measure the output of a process. It should not modulate or modify the output, rather it should carefully reproduce it; therefore, its gain ideally should be 1. Practically it might not be possible; when it is not possible, one may has to put a filter along with the sensor; in that case, the sensor gain might not be unity. But for each analysis of closed loop control system, it is convenient to assume the sensor gain to be one or unity, that is all in this lecture.