Advanced Control Systems
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Module No. # 02
Frequency Domain Based Identification
Lecture No. # 03
Off-line identification of process dynamics

Welcome to the lecture titled Off-line Identification of Process Dynamics. Earlier in the our in our earlier lectures we have seen relay control systems, inducing limit cycle outputs. And when the relay is substituted by an equivalent gain, then the analysis of closed loop relay control systems, become easy. In today's lecture, we shall see how off-line identification can be done using equivalent gain of relays.

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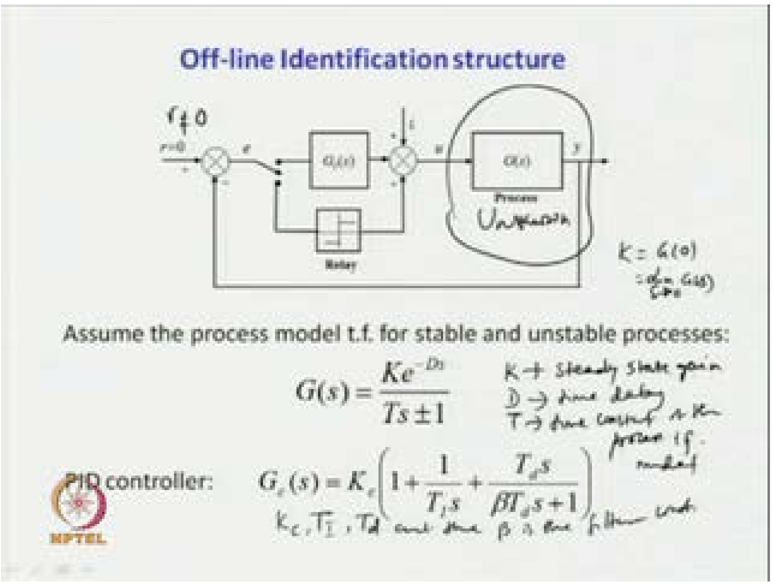

An off-line identification structure can be given like this, where r 0 equal to 0, when the relay is in action, whereas r 0 is not equal to 0, when the controller is in action. That means when the controller is in action, the process is in operation, then the relay test cannot be initiated, then when retuning of the controller is required, then we need to set the setting value reference input value to 0 r to 0. And disconnect the controller and put a relay in the feed forward path that is how off-line identification is done using relay control systems.

Now, for identifying specific transfer function models for process dynamics, let us assume a first-order plus dead time process model of the form G (s) is equal to K e to power minus D s upon T s plus minus 1. So, when plus sign is used in the denominator at that time we shall get a stable process model whereas, for the negative sign, we get unstable process model.

Now, in the process model, we have got three unknown parameters, the unknown parameters are K, D and T; K is the steady state gain steady state gain of the process, and K is also equal to G (0), that means when we take the limiting of s to 0 G (s) gives us the steady state gain of a process. Then D is the time delay of the process model whereas, T is the time constant of the process transfer function model. Let the controller be a PI PID controller given by G c (s) is equal to K c times 1 plus 1 upon T I s plus T d s upon beta T d s plus 1, where K c T i T d are the parameters of the PID controller and beta is the filter constant, derivative filter constant.

So, we we will not concentrate on the dynamics of PID controller, because we are going for off-line identification, where controller will be out of the loop, so we get no role to play. Now to identify the dynamics of an unknown process, let the process be assumed as the unknown, we do not know the dynamics of this process, rather the dynamics of this unknown process will be modeled by a first-order plus dead time transfer function model.

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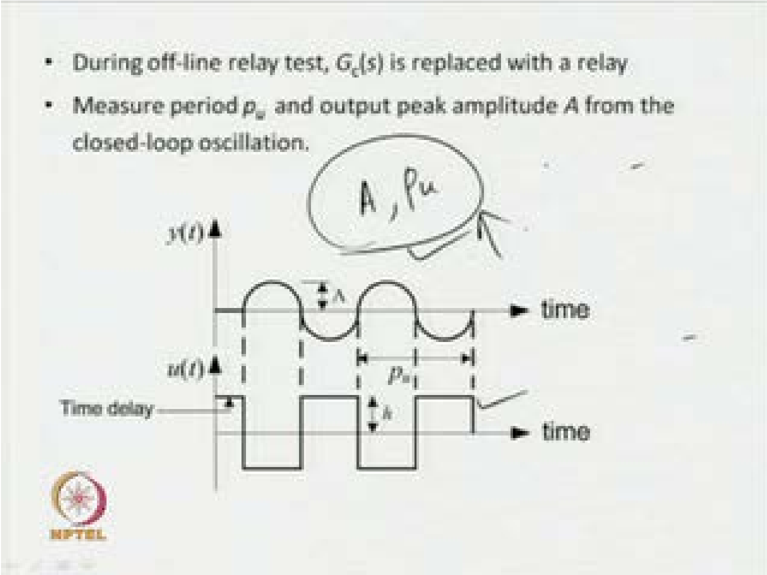

Now, for that during off-line relay test G c (s) is replaced with a relay, then we get limit cycle output, from the closed loop. So, the relay induces limit cycle output as shown here, where the output signal y (t), output signal has got some parameters; since we are getting sustained oscillatory output. Therefore, we can acquire or measure some information from the limit cycle output.

So, let A be the peak amplitude of the limit cycle output signal, so the A is the peak amplitude of the limit cycle output, then similarly, P u be the ultimate period of the limit cycle output. Ultimate period means nothing but, the time period of the output signal, then the upper waveform gives us a typical limit cycle output waveform for the relay control systems.

Whereas, the bottom one, the waveform shown below the upper one is nothing but, a typical relay output waveform this is the relay output waveform of the same period of the output limit cycle output; h is the peak amplitude of the relay output waveform. Where h is also nothing but, the amplitude of relay amplitude of relay often known as relay height and is the nothing but, a parameter for relay setting, h is we get from the relay setting.

So, when the autonomous relay control system is consider, we get some typical limit cycle output of the unknown process of this form and some typical relay output of this form. So, making measurement of some features of the limit cycle output, the features known as A P u of the limit cycle output it is possible to establish some relationship with the unknown transfer function model parameters, with the measurements. And then using the measurements it is possible to estimate the unknown parameters of a transfer function model, first-order plus dead time transfer function model.

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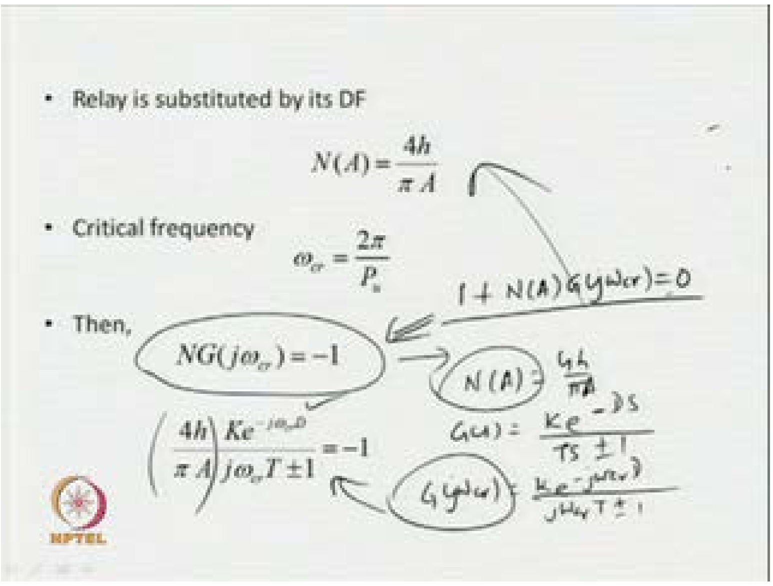

So, the relay is substituted by it is describing function for the analysis, the relay is defined by a function N (A) which is equal to 4 h by pi A, where h is as we know the relay amplitude; and A is the peak amplitude of the relay input, I can say relay input signal. So, from an ideal, for an ideal relay the describing function of the relay can be given as N A is equal to 4h by pi A. Next the critical frequency is defined as omega c r is equal to 2 pi upon P u, where P u is the ultimate period of the limit cycle output ultimate period of the limit cycle output.

Then since the characteristic equation of the relay control system, relay closed loop control system is 1 plus N (A) G y omega c r is equal to 0, this is the characteristics equation of the relay control system. Then using that we can write N G j omega c r is equal to minus 1, the same expression can be obtained from the fact that, limit cycle output is obtained, when the loop gain is equal to 1 and loop phase is equal to minus pi. So, the same can be transformed into some analytical expression form which is given as N G j omega c r is equal to minus 1.

Now, substitution of N (A) which is nothing but, 4 h upon pi A and G j omega c r gives us the equation 4 h upon pi A K times e to the power minus j omega c r D upon j omega c r T plus minus 1 is equal to minus 1, because N A is equal to 4 h by pi A as we have seen earlier at G (s) is equal to K e to the power minus D s upon T s plus minus 1. So, in frequency domain that can be written as G omega c r is equal to K e to the power minus j omega c r D upon j omega c r T plus minus 1. So, substitution of this N A and G omega c r over here give us this equation.

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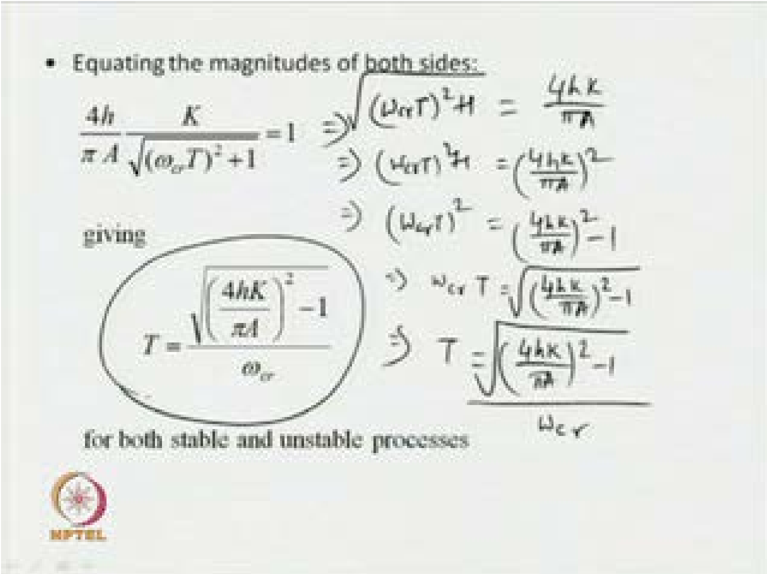

Equating the magnitude of both sides of the equation, we get 4 h upon pi A times K upon omega c r T square plus 1 root is equal to 1. So, for both the stable and unstable transfer function model, the magnitude of the analytical expression will be same. So, this can further be simplified as written in the form of omega c r T square plus 1 root is equal to 4 h K upon pi A implies omega c r T square plus 1 is equal to 4 h K upon pi A square.

Then next, that can be also written as omega c r T omega c r T square is equal to 4 h K upon pi A square minus 1, then taking the square root of that will give us omega c r T is equal to 4 h K upon pi A square minus 1 root. So finally, we get the expression T is equal to 4 h K upon pi A square minus 1 root upon omega c r. So, this is how we get the expression for the time constant of the transfer function model, the first-order transfer function model expressed as T is equal to 4 h K upon pi A square minus 1 root upon omega c r, this expression can be used for both stable and unstable process dynamics.

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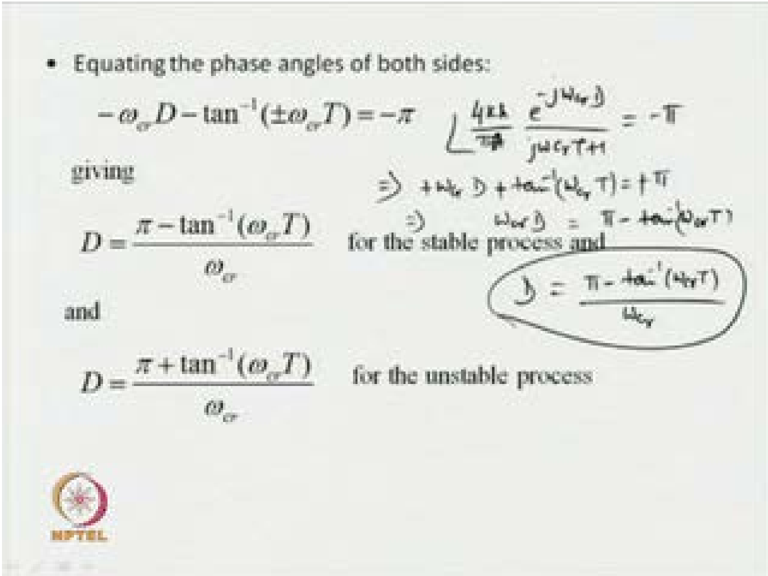

Next, equating the phase angles of both side, again we get we know that the phase angle of both sides means 4 K h upon pi A e to the power minus j omega c r D upon j omega c r T plus 1. Let us consider the stable process model first, so this angle should be equal to minus pi, because the loop phase is equal to minus pi, which can be written in the form of minus omega c r D minus tan inverse omega c r T is equal to minus pi. So, making all these minus to plus, now will enable us to write omega c r D is equal to pi minus tan inverse omega c r T, which will ultimately give us d is equal to d is equal to pi minus tan inverse omega c r T upon omega c r.

So, this is how we get the expression for the the second unknown parameter in the transfer function model of a stable process dynamics, the D time delay as D is equal to pi minus tan inverse omega c r T upon omega c r. So, extending the similar analysis for the unstable process, now we can get the expression for D as D is equal to equal to pi plus tan inverse omega c r T upon omega c r.

So, this is the way, we can estimate the unknown model parameters T and D T and D of the first-order plus dead time transfer function model, using the measurements of P u and A. Please keep in mind D and T, if we see T is now, a function of A and omega c r and omega c r is a function of P u. Therefore, making use of the measurements of omega c measurements of P u ultimate period and peak amplitude A, it is possible to estimate T and it is possible to estimate the this for stable and unstable processes.

So, from the analysis, we have found that with the measurements of peak amplitude and frequency of the limit cycle output signal, it is possible to estimate two parameters of the unknown transfer function model, first-order plus dead time model of a process dynamics.

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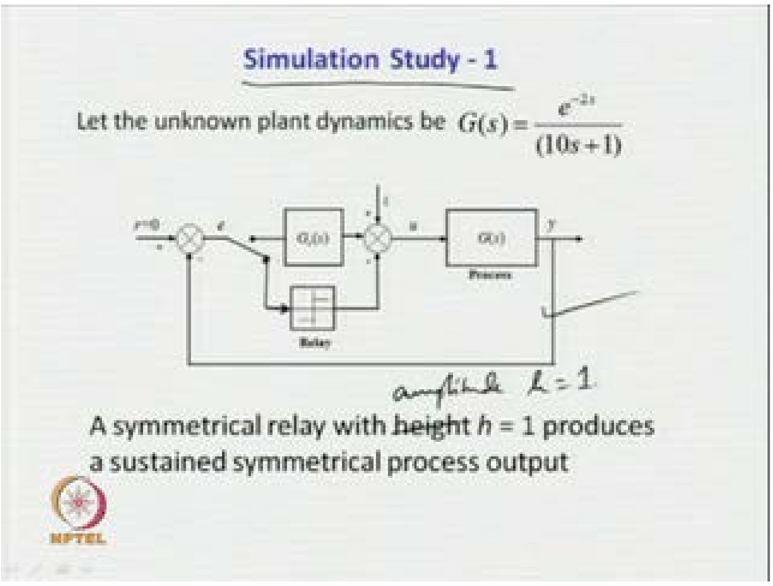

Let us, go for some simulation study and see, how accurate is our method; so in the simulation study one, let us consider the process to be process dynamics actual process dynamics to be G (s) is equal to e to the power minus 2 s upon 10 s plus 1. So, the actual process is assumed to have a time delay of 2 seconds, a time constant of 10 seconds and a steady state gain of 1. If this is the actual process has assuming that the actual process dynamics is not known, we shall put a relay in the feed forward path along with the process and make one relay control system. So, using the relay control system and with the setting of relay amplitude of h equal to 1 relay amplitude h equal to 1.

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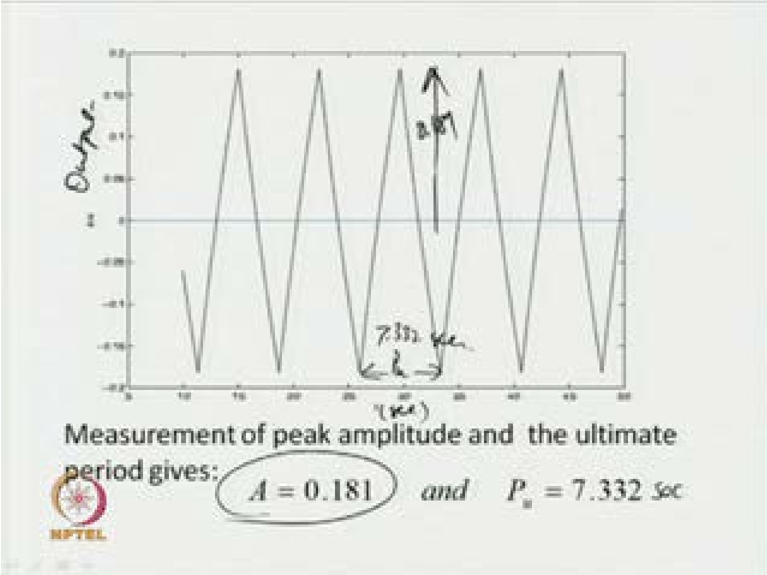

What we get we get a typical limit cycle output of this form, where this is x axis, this is the time axis, time in seconds and y axis is the output limit cycle output. Now we can make measurements the period of the limit cycle output, often measurement gives us P u to be of 7.332 seconds; similarly, the peak amplitude is found to be of magnitude 0.181. So, this is of value 0.181 and P u is of value 7.332 seconds.

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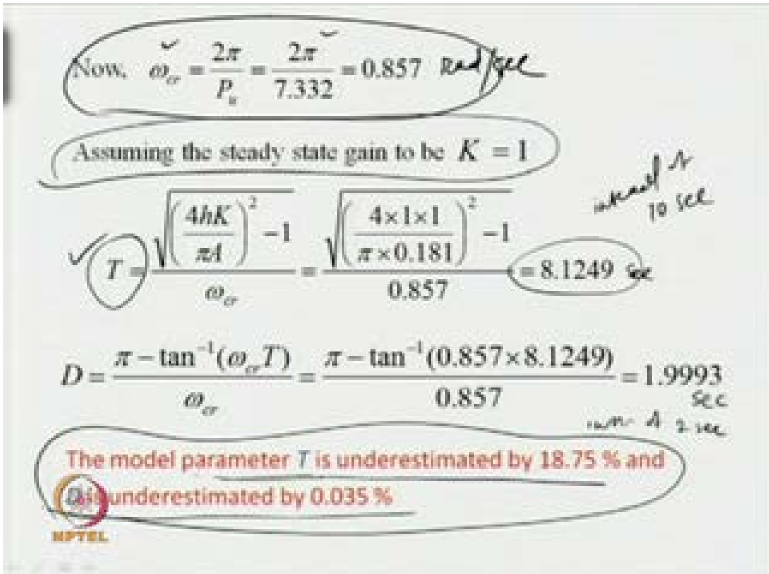

Then the critical frequency is calculated as omega c r is equal to 2 pi upon P u is equal to 2 pi upon 7.332 is equal to 0.857 second sorry radian per second. Now, the steady state gain is assume to be 1 as we know that using the describing function technique, we can estimate at most two unknown parameters of a process model.

Therefore, we have to make use of some assumption, because the first-order plus dead time process transfer function model has got three unknowns; the steady state gain, the time constant and the time delay. So, the steady state gain is assume to be known a priory or it can be obtained from some other tests, so assuming the steady state gain to be one K is equal to 1.

The T can be the time constant can be estimated as T is equal to 4 h K upon pi A square minus 1 root upon omega c r is equal to 4 into 1 into 1 upon pi into 0.181 minus square minus 1 root upon 0.857 gives us T is equal to 8.1249 seconds. Similarly, D is calculated using the measurements as D is equal to pi minus tan inverse omega c r T upon omega c r is equal to pi minus tan inverse 0.857 into 8.1249 upon 0.857 is equal to 1.9993 seconds.

Thus the process model parameters time constant is found to be of value 8.1249 seconds instead of the actual value of 10 seconds and the time delay is of value 1.9993 seconds instead of or in place of 2 seconds. Those are the actual plant parameters or the actual process has got the dynamics with time constant of 10 seconds and time delay of 2 seconds. So, the model parameter time constant is underestimated by 18.75 percentage and the time delay is underestimated by 0.035 percentage.

So, we can tell that the time delay has been estimated accurately, whereas, the time constant has not been estimated accurately. Since the relay has been assumed by it is equivalent gain therefore, there is estimation error in the identification scheme. If the relay is approximated by it is exact gain or if the relay is substituted by it is exact gain or you making use of the exact analysis of relay control system. It is possible to estimate the model transfer function model parameters accurately whereas, we have to scarifies some accuracy in the case of relay control system using some describing function technique.

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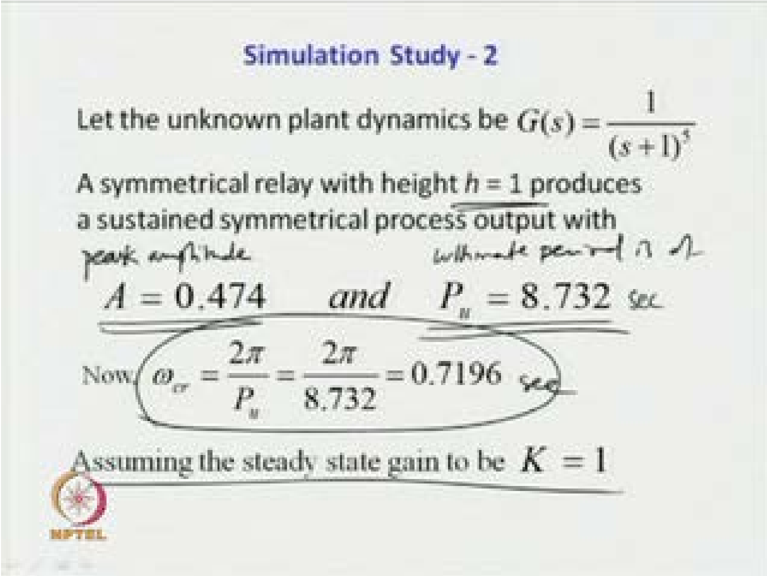

Let, us go to one more simulation study where the unknown plant dynamics is assume to be G (s) is equal to 1 upon s plus 1 to the power 5. So, in this case what we are going to do the actual plant is a plant all-pole plant with 5 repeated poles located at s equal to minus 1. So, the actual plant is something else. Whereas, we are going to estimate the plant dynamics by some first-order transfer function model.

What is that model, so we are going to estimate this dynamics by some equivalent model G m s of the form K e to the power minus D s upon T s plus 1. So, it is possible to capture the dynamics of actual plants by some transfer function models, not necessarily one has to assume the form of the transfer function as same as the plant dynamics.

In that case a symmetrical relay with amplitude h is equal to 1 produces a sustained symmetrical process output. And making measurement of the limit cycle output signal, we obtain the peak amplitude peak amplitude to be of A is equal to 0.474. And the peak and the ultimate period is of value 8.732 seconds, so the critical frequency is calculated as omega c r is equal to 0.7196 second.

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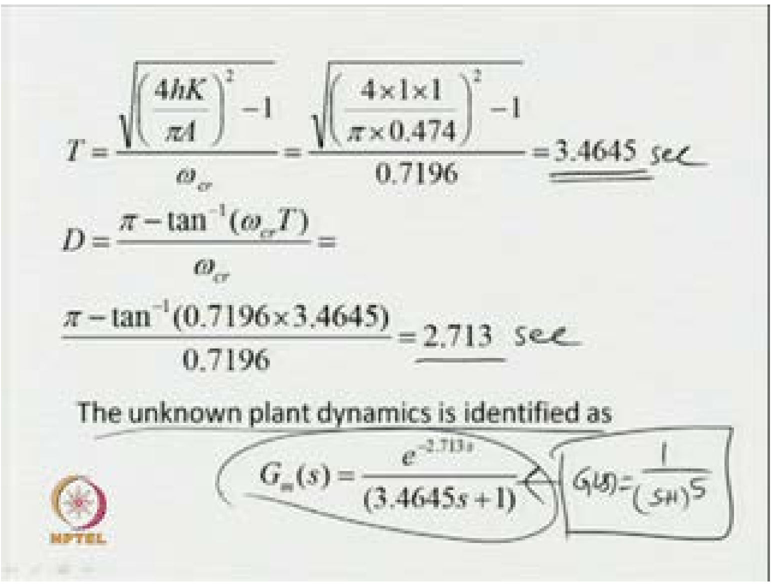

Again assuming the steady state gain to be 1 assuming the steady state gain to be one T is calculated as T is equal to 4 h K upon pi A square minus 1 root upon omega c r is equal to 3.4645 seconds. So, the time constant of the transfer function model is computed or estimated as T is equal to 3.4645 seconds. Now, the time delay can be estimated using the formula D is equal to pi minus tan inverse omega c r T upon omega c r, which is equal to 2.713 seconds.

So, the time delay of the first-order plus dead time transfer function model is found to be of the value 2.713 seconds, then the unknown plant dynamics is now represented by a transfer function model given as G m s is equal to e to the power minus 2.713 s upon 3.4645 s plus 1. Whereas, the actual plant dynamics is G (s) is equal to 1 upon s plus 1 to the power 5; so actual plant with the dynamics given as this has been represented by a first-order plus dead time model, with time delay of 2.713 seconds and time constant of 3.4645 seconds. Now, how to validate the accuracy of identification, for that what we have done?

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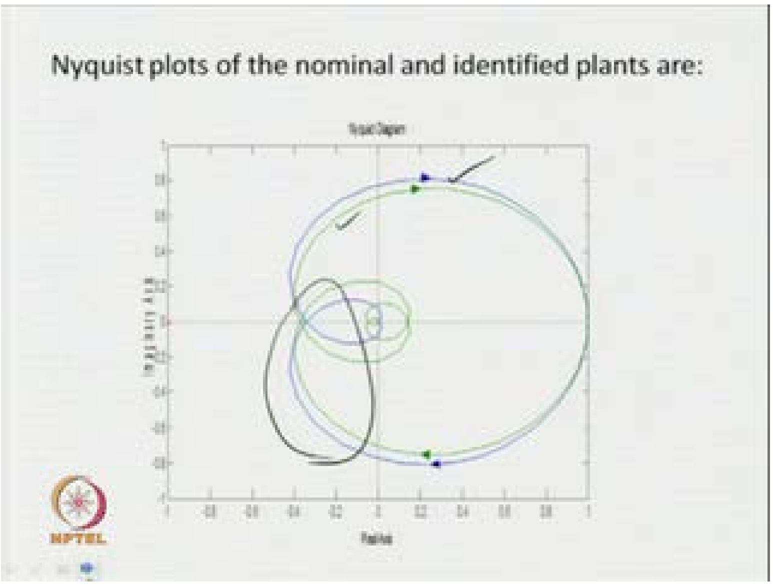

So, to ascertain the modeling accuracy to investigate the modeling accuracy, using the frequency response plots of both the actual and identified plant, we have obtained the Nyquist plot of the nominal and identified plants. So, the Nyquist plots of the original plant and the identified plants are plotted and shown over here; so there is no significant differences between the two plots then, one can conclude that the identified model truly represents the dynamics of the actual process.

So, basically we concern we have concerned about the part of the Nyquist plots in this range of frequencies and as we see there is no much difference between the two plots. Therefore, we can tell that we can assume that the identified transfer function model, represents the dynamics of the actual model actual plant successfully.

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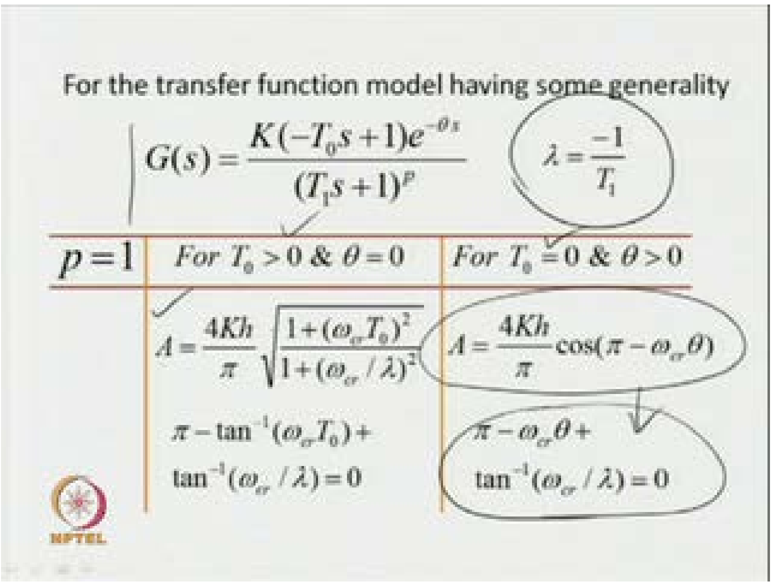

Now, for the transfer function model having some generality and given as G (s) is equal to K minus T 0 s plus 1 times e to the power minus theta s upon T 1 s plus 1 to the power P; also we can make use of the describing function analysis and estimate the unknown parameters of the transfer function model.

Now, here the the transfer function model involves a lot of parameters, the steady state gain K, time delay theta, here theta is the time delay of the transfer function model, T 0 is the time constant of the transfer function model. And T 1 is also one time constant of the transfer function model and P is the pole multiplicity a transfer function model as then for various values of P we get different type of transfer function models. And similarly, for a various values of theta and T 0 it is possible to get transfer function model with time delay and transfer function model with non-minimum phase characteristics.

Now, when lambda is assumed as lambda is equal to minus 1 upon T 1, when P is equal to 1 for the case T 0 is greater than 0 and theta equal to 0 theta equal to 0 means, we basically get the non-minimum transfer function non-minimum phase transfer function models. So, for those models one can establish equation or relations using describing function for the relay control system and the set of equations can be obtained as the peak amplitude can be given as a is equal to 4 K h upon pi root of 1 plus omega c r T 0 square upon 1 plus omega c r upon lambda square.

Similarly, this we get from the loop gain condition and similarly, the loop phase condition enables us to obtain an expression of the form pi minus tan inverse omega c r T 0 plus tan inverse omega c r upon lambda is equal to 0. So, basically we are able to obtain two relations, two equations using the describing function analysis.

Similarly, when T 0 is equal to 0 and theta is non 0, that means when the transfer function model is a transfer function model with time delay for that case a is given as 4 K h upon pi cos pi minus omega c r theta. And the phase condition of the relay control system will give pi minus omega c r theta plus tan inverse omega c r upon pi is equal to 0. So, in any case what we have found, we are able to get two equations using the describing function analysis.

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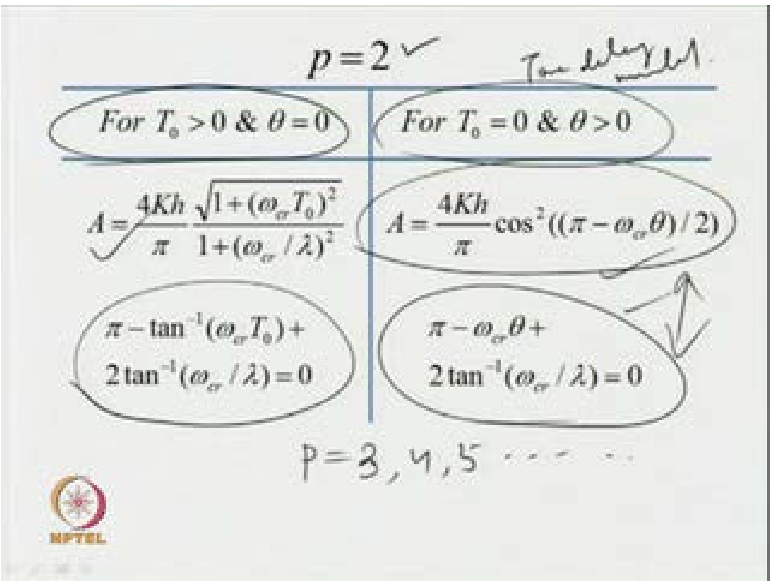

So, for higher values of P also we one can easily obtain similar expressions, when P is equal to 2, when the transfer function model is of second-order. In that case for the case of T 0 is greater than 0 and theta is equal to 0 the set of equations are obtained as A is this much and the phase condition gives us this equation. Now for T is equal to 0 and theta is not 0 for transfer function models, which are known as time delay models.

So, time delay models, then the two equations are A is equal to 4 K h upon pi cos square pi minus omega c r theta upon 2. And the phase condition will give us pi minus omega c r theta plus 2 tan inverse omega c r upon lambda is equal to 0. So, these equations can easily be obtained using describing function analysis and it is not difficult to obtain similar expressions for higher values of P. So, for P from 3 to onwards 3, 4, 5 onwards also, we will get very simple analytical expression of this these forms.

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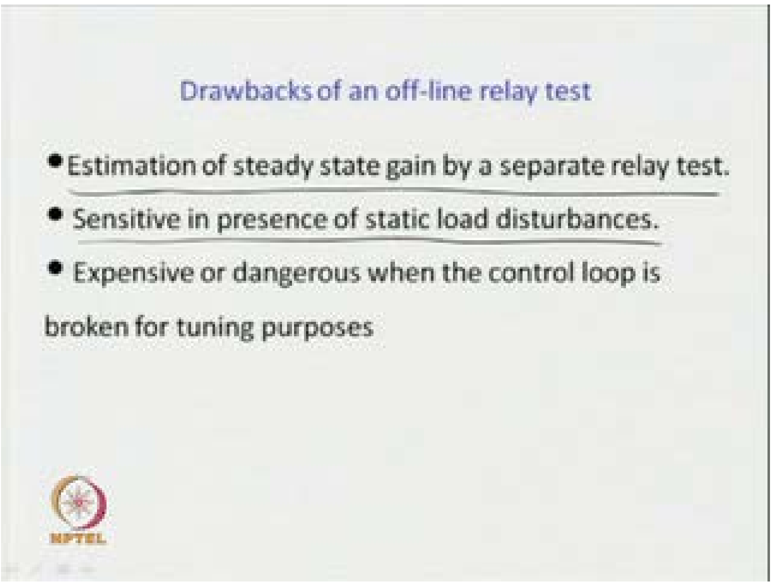

Now, drawbacks of an off-line relay test, what are the drawbacks an off-line relay test has, using the describing function the off-line relay test is found to give us only two analytical expressions; therefore, two unknowns of the transfer function model can be estimated.

So, basically we make use of the measurements and the analysis to estimate the time constant and time delay of a transfer function model. In that case it is required to estimate the steady state gain by a separate relay test or using some other analysis, because we cannot estimate three unknowns using the two equations, we developed for the relay control system. So, one has to assume either assume the steady state gain to be known a priory or make use of other tests to estimate or obtain the steady state gain value. So, that is one of the major drawbacks associated with an off-line relay test.

Now, second problem with the off-line relay test is that, it is sensitive to the presence of static load disturbance; how that is show we shall see by going back to some earlier slide, where we have the structure for relay control system.

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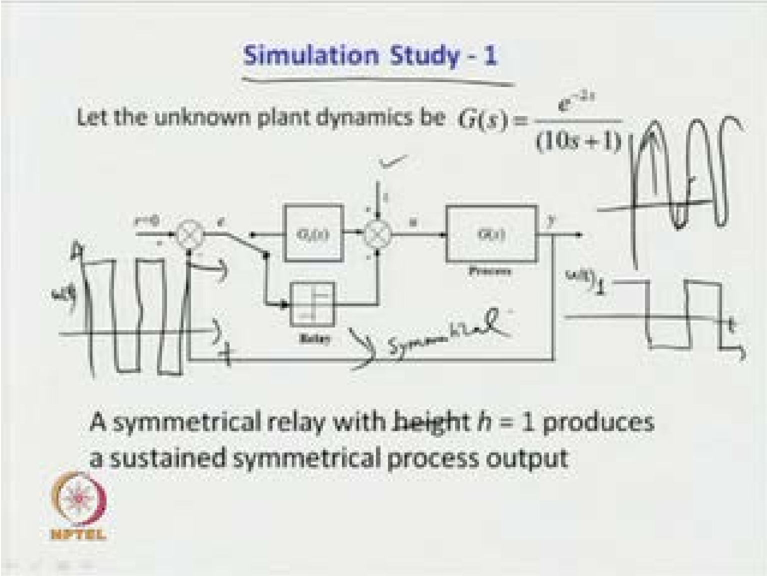

Now, this structure shows that when the relay is connected with the process unknown process, when some static load disturbance is presents present. In that case what will happen u the process input will be a symmetrical, as we know when L is equal to 0 what will be the form of the u; u will assume some symmetrical output waveform of the form some square or rectangular pulses.

So, this is what we have T and this is our u T, this is what we get when L is equal to 0 when the static load disturbance is equal to 0. Suppose L is of some magnitude and the relay amplitude is 1 therefore, magnitude of this signal is equal to 1, now when L is equal to 0.5, then this 0 point this 0.5 will get superimposed with this signal and ultimately it will get elevated. Therefore, we will have some asymmetrical relay output signal of the form shown over here.

So, this will continue this is the time and this the u T, so for the for this case for this situation what will happen when the input signal to the process is asymmetrical the output the limit cycle output also will be asymmetrical. Definitely it will be asymmetrical but, of the same period as well; so we shall get some asymmetrical limit cycle output asymmetrical limit cycle output from the system.

So, although the relay is symmetrical the relay is symmetrical whereas, the limit cycle output signal is asymmetrical. Now how to make use of those techniques the analysis we have made earlier all those will fail because we cannot get correct measurement of the peak amplitude. Now we have got two peaks one positive peak and one negative peak of different magnitudes; similarly, the period we can measure but, when we reset to half period there will be a lot of difficulty. So, again measurement of period will be there but, we will not get the correct period, what is required for the symmetrical relay.

So, when the asymmetrical output limit cycle output is obtained, we do not know where from the asymmetricity is coming. So, is it due to asymmetrical relay or is it due to disturbances that will actually create problem we may not get correct information about the process dynamics. So, that is one major difficulties associated with off-line relay test, so the off-line relay test is subjected to limitations (Refer Slide Time: 37:50) and inaccuracies, when the static load disturbances are present.

And in practical real time systems it is very difficult to avoid static load disturbances or some form of the disturbances will always be there therefore, the off-line relay test may give us in inaccurate estimation of transfer function model parameters.

Now, third point is often it is dangerous and also expensive to break the control loop for the purpose of tuning only, for the purpose of PID controller tuning. When the loop is broken then the control operation is disrupted; the normal operation of the system gets disrupted, which is not desirable for many real time systems. What is desirable rather that often, it is desirable to tune controller under tight continuous closed loop operation.

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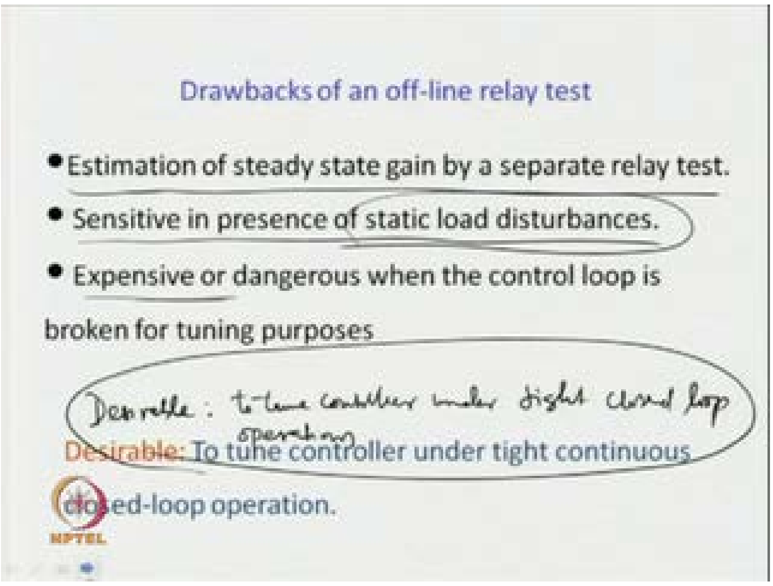

So desirable is to tune controller under tight closed loop operation and this is what we are not going to get from off-line tuning schemes.

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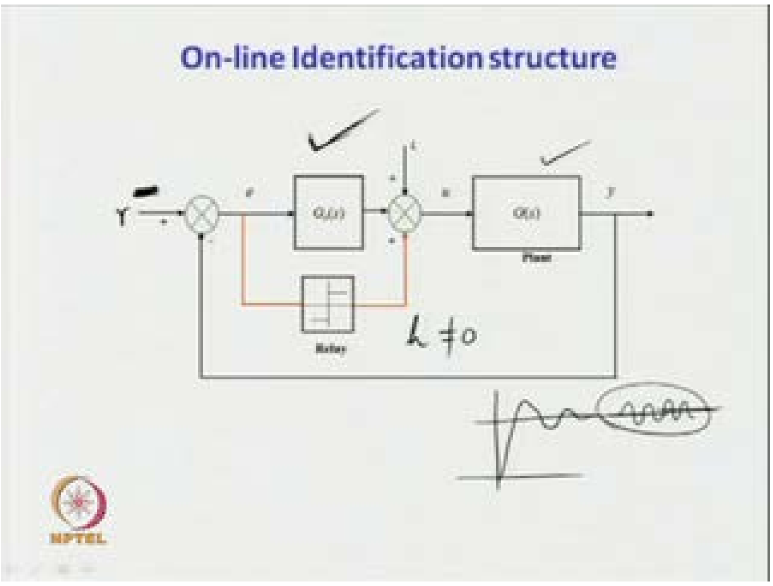

Next, we shall consider some on-line identification structure to overcome the limitations associated with off-line identification schemes; we shall consider an on-line identification structure. Where this r T is not necessarily has to be 0, so I can write it can be non 0 also this is your r T or reference input r simply. So, this gives us the structure of an on-line identification scheme.

What we see what is the basic difference between the earlier structure and this structure a relay has been connected in parallel with the controller. A relay has been connected in parallel with the controller and the controller remains in actions throughout the operation of the real time system real time process. Whereas, whenever there is requirement for retuning the parameters of the controller, what we can do the process information can be acquired by setting some relay amplitudes.

So, when the relay amplitudes h is equal to 0 when the relay amplitudes h are 0 at that time, the controller is in action and the output of the plant can be of the form like this, we do not get limit cycle output when relay is not in action.

Whereas, when the relay is in action now when the relay amplitudes are not equal to 0 at that time, we will get the output of the form limit cycle output, superimposed over the steady state output of the process this the beauty. So, during this time we make measurements of the output limit cycle output signal and estimate the plant dynamics model parameters. So, plant model parameters and based on the model parameters the parameters of a controller are set, the parameters of a controller are set and this is how on-line identification and tuning is done in real time.

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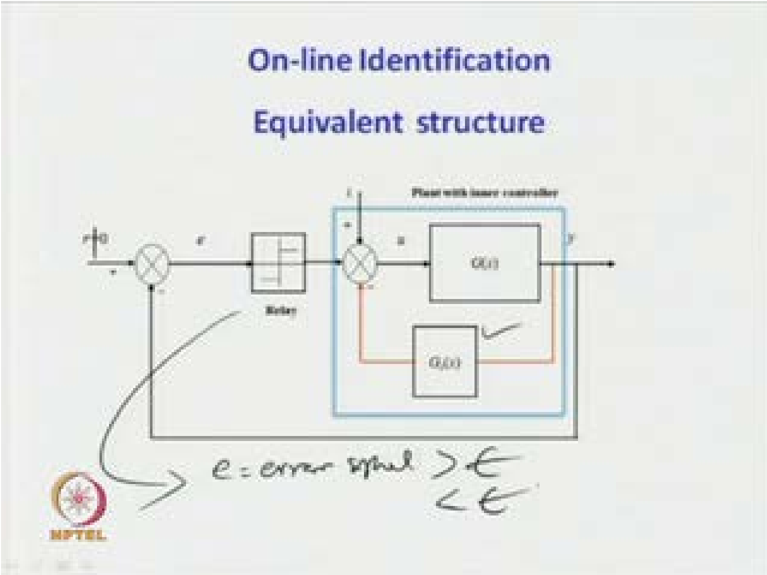

Now, we can represent the on-line identification structure by some equivalent diagram; if you look carefully, then in that case again r is not equal to 0 then the G (s) is now, subjected to some inner feedback with a controller G c s. The earlier feed forward path controller G c (s) now appears in the feedback path; so G (s) is now having some inner loop controller G c s. And relay basically sees or experiences the process connected with an inner controller, so the relay is experienced or experiences or sees a I can say controlled process a process with a controller in the loop.

Now, in contrast to the off-line control scheme or the conventional relay control scheme, the relay is subjected to a closed loop system. Earlier the relay was subjected to the process dynamics only whereas; in the on-line identification scheme the relay is subjected to a process with a controller in the loop. Therefore, it is possible to estimate more than two parameters from this scheme also with proper use of the or with proper measurements of the limit cycle output signal, it is possible to make more measurements from the limit cycle output or the output of the relay control system. And it is possible to estimate more than two unknown parameters of a transfer function model.

So, basically in on-line identification scheme has got advantageous over the off-line identification scheme, in the sense that it the planned operation is not disrupted. So, we will have normal operation of the plant and the relay heights are to be or the relay amplitudes are to be chosen suitably such that the plant operation is not affected at all. So, one can put some conditions depending on the magnitude of the error signal e e is the error signal.

So, whenever the error signal is greater than some threshold value epsilon that time only relay will come into picture will be in action and induce limit cycle output. And when the error signal is less than some threshold value there is no need for retuning the PID controller parameters.

So, this is the beauty of the on-line identification scheme, now using the on-line identification scheme a suitable controllers also can be designed. The form of the controllers also can be decided often; so those issues will be discussed in the next lecture.

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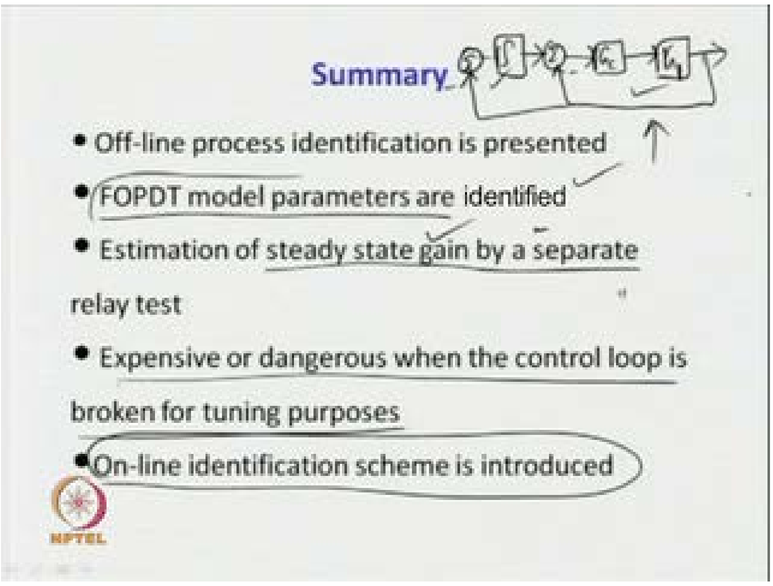

Next, we shall go to the summary now, what we have seen in this lecture off-line process identification is presented. So, an off-line identification scheme is presented and it is found that it is possible to estimate two unknown parameters of a transfer function model using the describing function gain or using the describing function analysis of a relay.

Now first-order plus dead time transfer function models can be estimated or obtained using the measurements made on the limit cycle output, not only first-order plus dead time models. But, also we can estimate we can obtain transfer function models of various forms and those are nothing but, non-minimum phase non-minimum phase transfer function models and higher order time delayed transfer function models. In that case what we will have second-order plus dead time transfer function model, third-order plus dead time transfer function model and so on.

So, it is possible to estimate two unknowns parameters of non-minimum phase transfer function models or say first-order plus dead time transfer function models or second-order plus dead time transfer function models or third-order plus dead time transfer function models using describing function.

Next now, it is not possible to estimate accurate values for the steady study gains using off-line relay identification scheme. So, estimation of steady state gain has to be done by some separate test or by some other techniques; so this is one crucial issue and there is limitation with the off-line relay test mainly in estimating the steady state gains.

Now, coming to the next point as we have discussed often it is dangerous and expensive to break the closed loop operation for the sake of tuning of controllers and to overcome that we have introduced on-line identification schemes. So, on-line identification schemes can be of different types one such on-line identification scheme has been introduced. We can have other type of on-line identification scheme as well where the scheme can be given in the form of suppose a relay outside the closed loop, then we will have the controller the process, inner feedback and then, we can have the feedback negative feedback to relay.

So, this can make a probable scheme for on-line identification also here, in this case what is happening, when the relay amplitudes are 0, we have got the normal operation of the plant or process with a controller. And for nonzero heights of the relay or when the relay amplitudes are not 0, at that time the output will have some limit cycle waveform. And this also can make a probable candidate as I have told for the on-line identification scheme.

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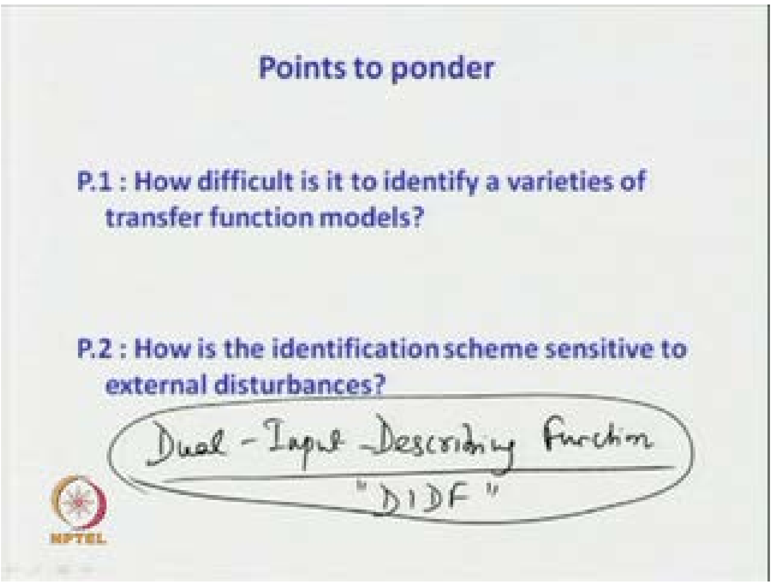

Some points to ponder, how difficult is it to identify a varieties of transfer function models, describing function based methods enables one to estimate two unknown parameters of a transfer function model. As we have seen the model can be of a general form or of any form, but only two unknowns of the transfer function model can be estimated using the describing function analysis.

So, some other tests or multiple relay tests might be used, might be made to identify a varieties of transfer function models. The second point how is the identification scheme sensitive to external disturbances? As we have seen, when we have got a static load disturbance then the limit cycle output become asymmetrical, in spite of using asymmetrical relay in the relay control system. And asymmetrical relay output may not give correct information of the process dynamics; to avoid that, what is to be done as far as possible, we should try to get symmetrical limit cycle output and we should try to take measurements from the symmetrical limit cycle output.

And for that, one has to make use of some other scheme and one has to go for on-line identification scheme, also it is possible to make use of another analysis technique known as Dual Input Describing Function analysis - DIDF, DIDF analysis for the relay control system, which is subjected to external static load disturbances. So, in in this case, it will be possible to estimate more number of parameters, and also it will be possible to it might be possible to estimate accurate values for the transfer function model parameters that is all in this lecture, thank you.