Advanced Topics in the Science and Technology of Concrete
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Closed-Loop Testing Part 1

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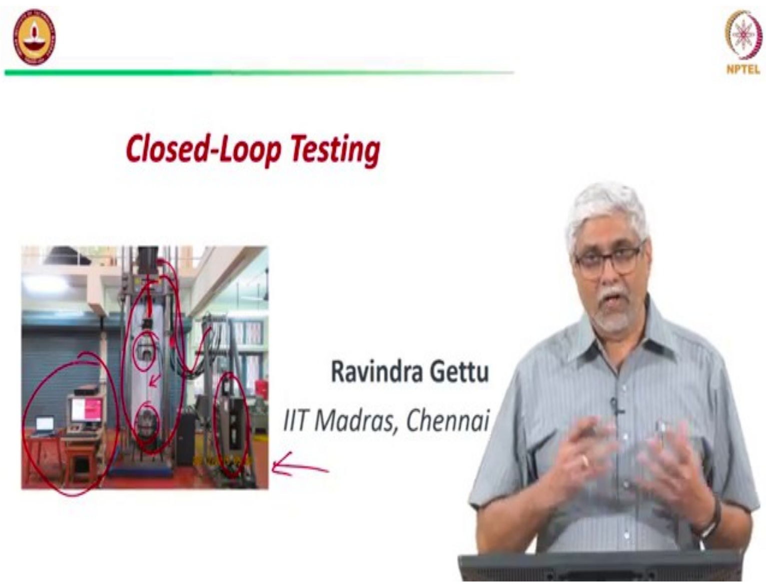

Welcome to this lecture on closed-loop testing, I am going to talk to you about what is closed-loop testing, what is it used for and give you some examples and what we will have in this block is, see some videos of test actually being conducted, there will be a set of four or five videos, I will talk to you about the test during this lecture, so at this stage and later on you will see the research scholar explaining, why they do this test and how they do that.

So above you can see a testing machine, this is the frame which have the actuator, so what you see there is the actuator and then you have grips for holding on to the specimen here that is being tested, then the hydraulic power or the oil pressure comes in through the hoses and there you have a manifold and to that a pump is attached and everything is being controlled by system which could be computer-based or it could be larger, having a larger controller, so we are going to be looking at systems like that and see how they act and what is this closed-loop and what are the advantages?

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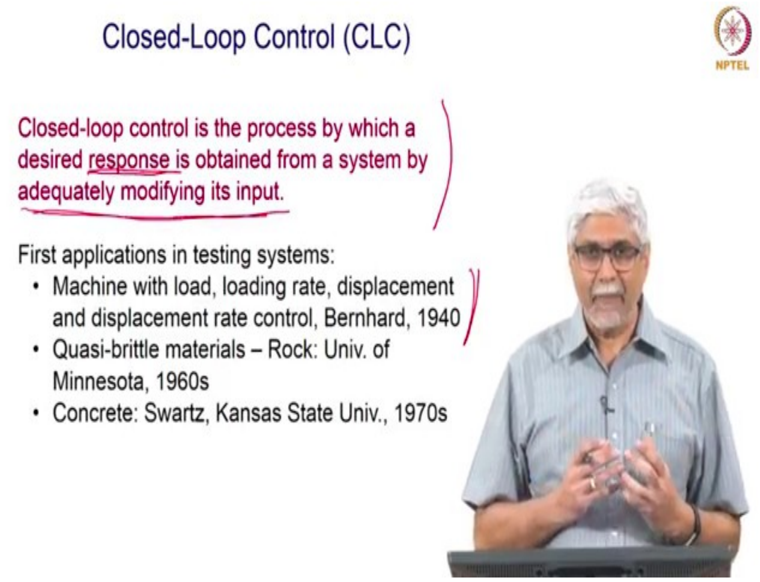

So, closed-loop control is very simple to think of, it is to get what you want out of a system, human beings are very much closed-loop control like, if something is hot as soon as you touch it, you react by taking your hand off or when you have a hot water, you slowly touch it to see how hot it is and immediately you know that you have to you move your finger and adjust the taps to give you the temperature that you want, so basically your body is closing the loop, so what we want is a system to know what response is required and make the adequate changes so that, this response is obtained in the test.

So we can say that closed-loop control is the process by which a desired response, the response that we want in a test is obtained from the system, here the system is the testing machine and the specimen also and what the system does, is keep modifying its input to give us the response that we want. So, the system itself is modifying the response, modifying the output to give us this response, so that is what is called closing the loop and the first applications of testing, in testing systems were done in 1940s, where a machine was set up by Bernhard, which could control the load, loading rate, displacement and displacement rate. And more recently this widespread use of closed-loop control system happened in Minnesota in 1960s and concrete by Swartz in Kansas State University in 1970s.

So, they were the ones who started using these types of systems to control test on rock and concrete which are brittle materials but we would like to know what is the way did this material fail, so machines were created or machines were set up, so that you could get the response in a stable manner.

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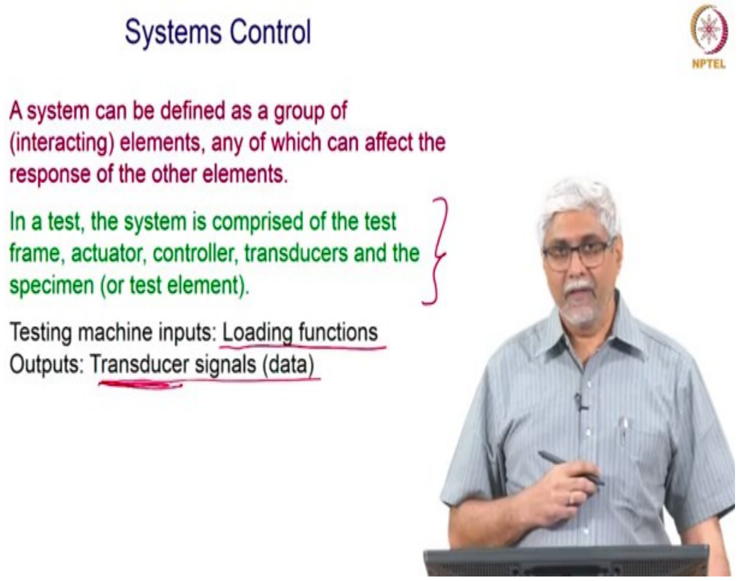

We talk about systems and as I have told you for the general-purpose, a system is a group of elements which are interacting, which can affect the response of the other elements, like if some the behaviour of one element changes, then the other elements also are affected, so that together is what we call a system and in terms of testing, a testing machine the system is the test frame, shown in the first slide, that have the actuator, actuator is what applies load or displacement, the controller tells the actuator to how much to move, transducers are sensors or elements that can give us the response or measure the response and finally a specimen, which is your test element, that you want to subject to the loads and find out the response.

So what we tell the machine is a set of loading functions, we would say that the loads has to increase in a certain rate, the load has to increase, stop, decrease, the strain has to increase in a certain way or you will have to cycle the displacement or strains, all these are loading functions, so we tell the system that this is how the test should proceed. The outputs are what you read out, those are the data that you get for further analysis and for understanding the behaviour, these come as signals from the sensors or transducers that we can placed on the system, on the specimen between the specimen and a reference in order to know how much the specimen is displacing, straining, moving, rotating and so on, so those are done by transducers which will tell us, if we are getting what we want that we have define with the loading functions.

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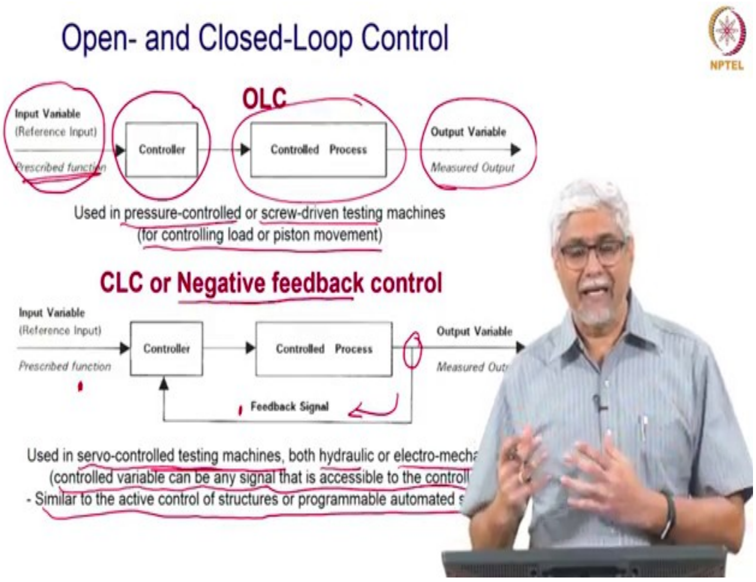

So, we look at what is the difference between open loop and closed-loop control. There are many systems, many testing machines which are open loop, where there is no feedback going from a transducer into the controller. So you will have a function that we prescribed, say that the displacement should increase in the certain rate or the load should keep on increasing, so the controller picks up whatever function we have put and defines a set of signals that it control the process and the test goes on. And finally we can get whatever we want to measure, using the transducer that you want, so if you have a system which is keeping on increasing load, you would have seen in some labs where your testing cube of concrete and you apply load and suddenly the concrete explodes and fails because the machine has been told that load has to be kept on increasing, the specimen cannot handle more load so it breaks or the same thing could happen with displacement.

So lot of pressure controlled systems, where we have a pump which is keeping on increasing the pressure so the load keeps on increasing or something that is screw driven testing machine, where we have a actuator that is moving up like a screw , so these are systems which only control load and piston movement, do not give any feedback to modify how the test is going to be done as it is going on, so these are open loop control systems, there is no closed-loop, there is no closing of the loop, there is no feedback going back.

Now in the closed-loop controls systems or what is also called negative feedback, because the feedback goes back to the controller. We have the same as above but you see that, there is a transducer or a set of transducers or a signal that is derived from a transducers output, that is fed back to the controller, so the controller now knows how the test is going on or the response and it checks whether the feedback is matching the function and modifies the signals so that the process is controlled as it should be.

So these are generally called servo-controlled testing machines, they could be the hydraulic or electromechanical, we look at these carefully and the variable or what we control as a signal is called the control variable, we are saying that this variable should change in a certain way, it could be anything that is measurable, it can be a combination of measurable quantities also, we will look at examples later. So this is very similar to anything that has active control say of structures or any programmable automated system like the cruise control on a car is closed-loop control, the car knows how fast it has to go and it keeps changing its gears to keep moving in the same speed or a programmable washing machine also, depending on the speed it should go, it provides more energy or less, so anything that is getting some feedback and adjusting itself to go in a certain way is a closed-loop control system.

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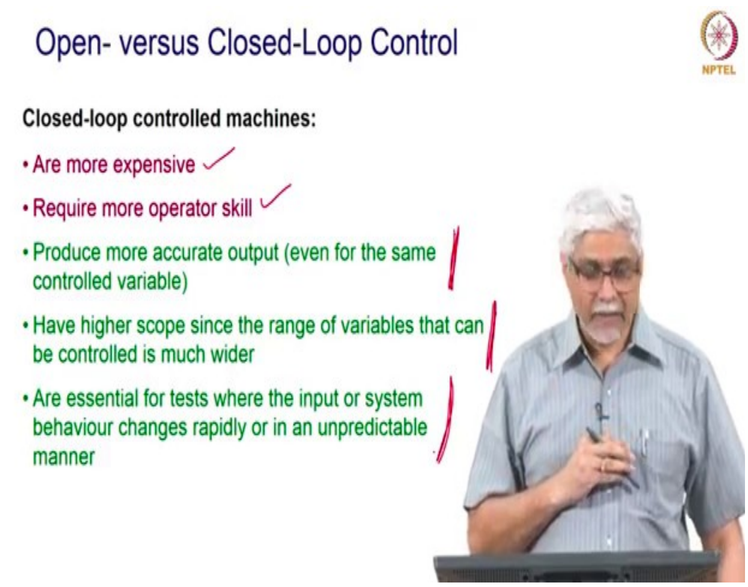

Closed-loop control systems are better but why are they not used all the time, because they are expensive, they require more operator skill, these are not machines that you just press the button and it works, you have to understand how these machines have to be set up, we have to know what is the signal, how to adjust the signal, I will talk about it in the next few slides a little bit more detail, they can give more accurate output, this is the reason why we want to use it, we have a machine which is closed-loop control, it will give us more stable response with much less variations than in open loop system, even though the controlled variable is the same, even though we are saying it is in load controlled or displacement controlled, you get better, more accurate, more reliable data from something that is closed-loop, in a testing machine that is closed-loop.

You have our range of variables that can be controlled, you can control strain, you can control the strain rate, you can do a lot of things, anything that can be measured or is a combination of measurements can be used as the variable, so the range or the scope is much more than what you would have with an open-loop system, these are very much essential where you have changes that can occur very rapidly, like I talked about the concrete cube, so when we are testing concrete, beyond a certain point the specimen deformed so fast that the machine has to react very fast, otherwise you lose controlled and you have this crushing or this explosive failure that we have seen or similarly when you have beam unreinforced concrete, testing it beyond a certain point the crack propagation is so fast that the specimen has to break, if you are not able to control fast enough.

So here you can imagine that you are pushing, but when the specimen is breaking new either push less slowly or you pushback, take the actuator back so that it can deforms slower and does not suddenly break apart , so that is what is the main advantage of a closed-loop control system, where you want to get behaviour during failure which you cannot get in open-loop.

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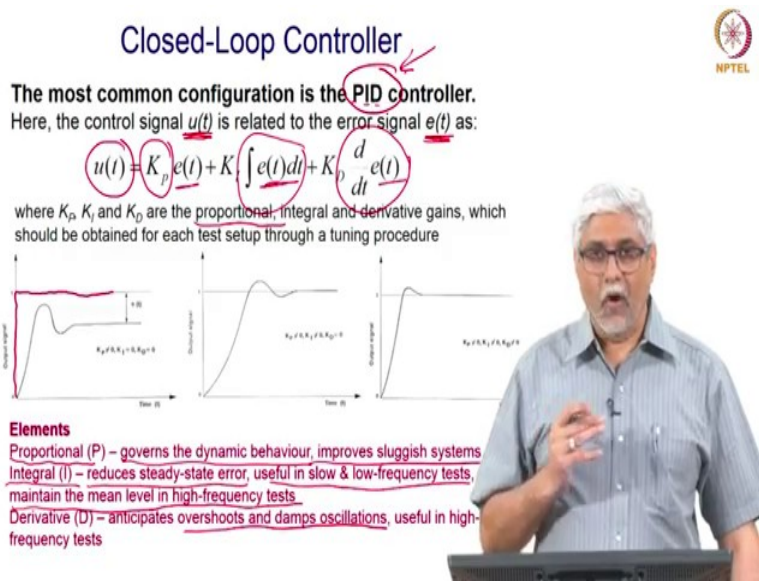

So, for this we have to understand a little bit how this really works, so there are many controllers, the most common or the basic control is called the PID controller and it stands for the three parameters which control or provide the control. They are proportional(K_p), integral(K_i) and derivative(K_d) and I will explain how each of these works, so imagine that we want to control the test in a certain way and u(t) is the control signal which is being given to the machine, if the machine or if the specimen is not responding as it should, the difference is the error signal i.e. e(t), so the controller is checking all the times, what is the actual displacement? What is the displacement I wanted to get and this is the error, this displacement could be something else also, it could be load, it could be strain, it could be rate of displacement, so it is always checking what did I want? What am I getting? The difference is the error and it modifies the control signal in terms of this,

$$u(t) = K_{\mathrm{p}} \underline{e(t)} + K_{\mathrm{i}} \int_0^t \underline{e(t)}\, dt + K_{\mathrm{d}} \frac{\underline{de(t)}}{dt},$$

so above is the error, the proportional multiplies the error with a certain constant 'K'.

So suppose I applied, I wanted to get a square wave , I wanted to get a sudden change in the displacement but I am getting something like shown in above image, then the proportional is adjusted to bring it up, so this multiplies the error with something, so if there is a big error that is immediately decreased by this proportionality, it brings it up fast that is what the proportional does.

What is the integral do? The integral looks at the area under the error time curve, it looks at how the error is changing with time and it tries to make sure that there are less oscillations about the mean, that it stabilises fast enough, goes to this curve fast enough without oscillating.

The final is the derivative gain which looks at the slope, it makes sure that you do not have these lot of jumps and you stabilise without much change in the slope, so the proportional helps to govern the dynamic behaviour, if you want things to move faster, if you want the system to react faster, we play with the proportional gain or proportional constant, it improves what are called sluggish system, like if the machine is slow in reacting you want it to react fast then you increase the proportional but if you increase the proportional too much, then it could break the specimen because it reacts too fast, so there is an optimum of how much could be the proportional gain.

The integral is good when you have fatigue test cyclic loading because it looks at something which should remain constant but is oscillating, it tries to change, it reduces the steady state error. If you have a test which should maintain load constant but you see that it is oscillating then changing the integral gain affects that, so it is useful in slow, low frequency test and it is useful to maintain the mean level in high-frequency test, so if something should be constant but you are seeing that its oscillating then we have to change the integral gain.

The derivative gain looks at damping oscillations. Damping oscillations is useful in high-frequency test because we do not want a lot of overshoots, we want to maintain the feedback as close as possible to what we want, so these are the three parameters mostly in the tests that we do in the lab, the proportional(K_p) is the most important for long-term test, see if you are doing the creep test or a cyclic test then the proportional(K_p) is important, when we are doing a lot of variations fast test then maybe the derivatives becomes important, so these are the para meters that we play around with in a PID controller, so these are settings that by experience or by some procedure we can derive.

What is often done is you set up an oscilloscope, put a square wave on the specimen, a loading like a square wave and see how it reacts and then you play around with a PID so that you get the signal that you want. Now modern systems can automatically do it, there is a function for calibration and you tell the machine that it is okay, it is safe to apply load over a certain value and the machine tries to optimise these parameters by putting different functions and waves on, so this give you some idea what is a PID controller and that you have to learn to optimise the controller when you have a closed-loop system.

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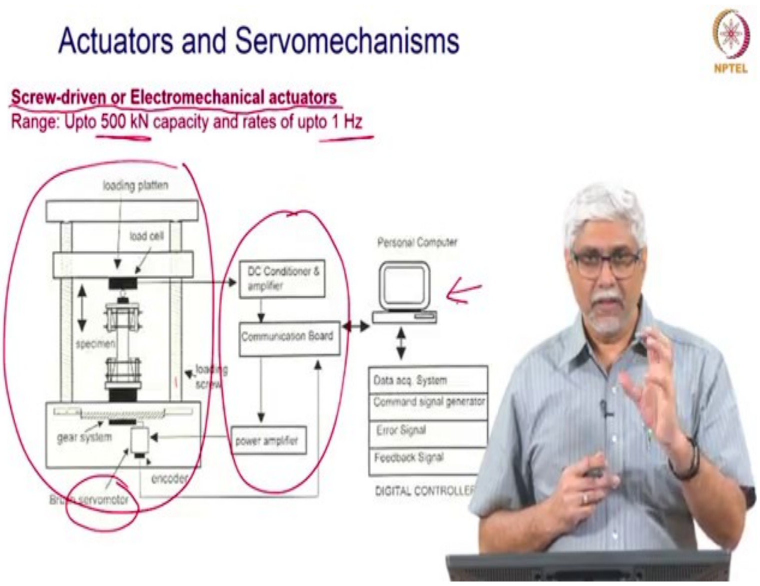

What are the other parameters or what are the other components of a servo-hydraulic or a servo-mechanical system? First let us look at what a called screw driven or electromechanical actuators, here you have a actuator that is moving up and down because there is a motor which is pushing it up and down, these are systems which are usually available only up to about 500 kN, these are smaller load machines, they cannot go very fast up to say about 1 Hz, if you want to do a cyclic loading beyond 1 Hz this machine will not go .

So as in the servohydraulic systems you have a frame something that the specimen, the actuator can react against, so you have the columns of the frame and then you have the top and bottom plate and then you have the system for applying load, in this case you could even have the columns moving up and down, turned so that the plate at the bottom, at the top plate goes up and down and applies the load or releases the load and here you have the specimen and the servo hydraulic, servomechanical system uses a servomotor with an encoder to tell how fast or how slow the motor should turn and depending on this the specimen is applied more load or less load.

So you have a system here which is doing the control and you could have something like a PC which is giving the function , so in a servo mechanical system we have an actuator that is driven by a screw, so it can go up and down, it has been pushed up and down just by using a motor to turn a screw which will push the actuator up-and-down.

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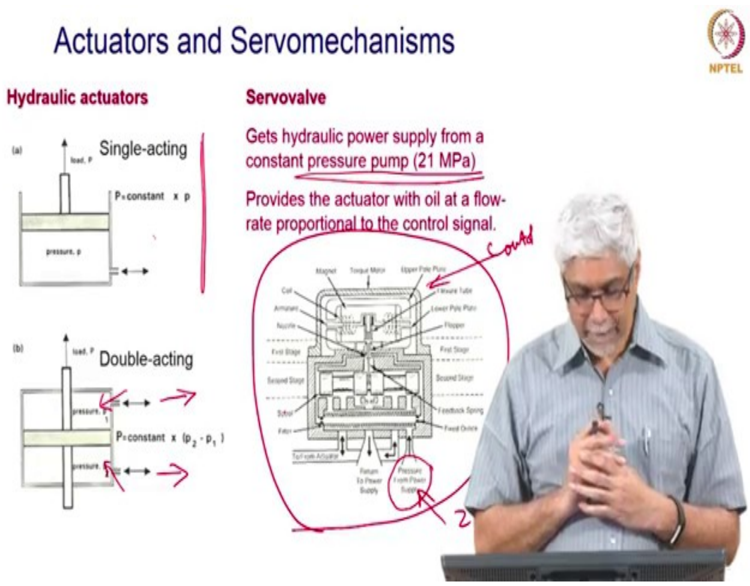

More common servohydraulic systems which have hydraulic actuator, there are two types of hydraulic actuator, the most common which we use in most purposes is a single acting actuato0,r where you have a chamber with oil under pressure, then you have a piston that is pushed up depending upon how much pressure you apply, more pressure, more load is applied and the piston can go up, the single acting actuator only goes in one direction, it has to depend on gravity or something else to push it back, however a double acting actuator can go either way, it can push one way or the other because oil can go in to the chamber from one way and come out or go in other way , so most servohydraulic systems will have double-acting actuators because we want the piston to go in one direction and maybe stop and even reverse fast enough and not just depend on gravity to do this.

So a server hydraulic system will have a double acting actuator and these ports for the oil are connected to what I call the brain of the servohydraulic system which is a servovalve, so the servovalve is getting the signal from the controller, so the comptroller is somewhere here and it is telling the servovalve to send in more oil in one port or the other and how it does is, it moves the pool which is connected to a pump, so oil is coming in as shown in above image, at the constant pressure of usually about 21 MPa , so the pump is not changing its pressure, in a single-acting actuator you have to change the pressure to apply more load or less load but here the pressure is constant, the pump is always running at 21 Mpa .

The variation whether the piston goes up, fast, slow or goes back is how much of oil is going into one chamber or the other and this is decided by a servovalve, it is a small apparatus, here actually it could be the size of what is shown in above image itself or it could be slightly even smaller, so the pressure is coming in with 21 MPa and there is a return which is going back to the pump and to the actuator pipes are connected. So depending on whether there is more oil going in, oil removed, the piston is going up or down, that is the function of the servovalve, so the servovalve can go faster or slower depending on whether it can react fast enough, or larger servovalve can react faster, it can send more oil through , so the servovalve is sort of the brain which is getting the signal from the controller, an electrical signal from the controller and sending more oil or less oil to one port or the other depending on this signal .

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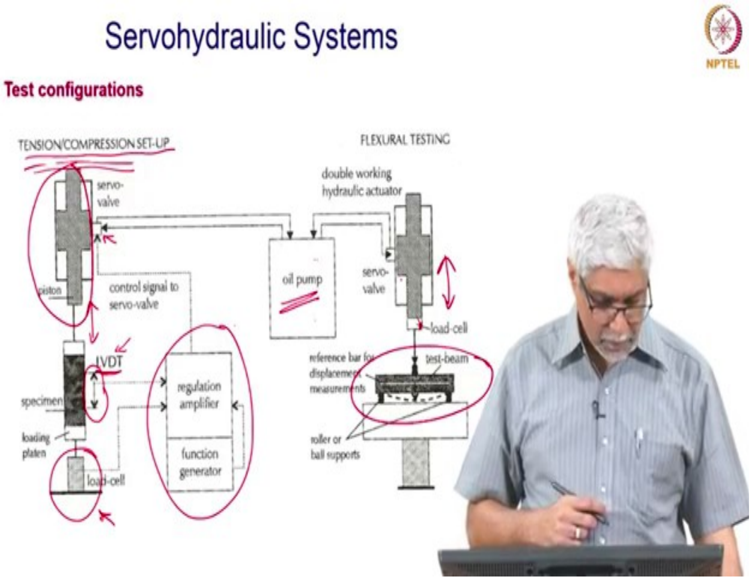

So this fits in to the rest of the configuration, suppose you have a testing machine which can be used in tension and compression, you will have the piston, the servovalve sits on the piston or next to the piston and extending oil into the piston one or both of its ports and therefore the piston goes up or down, so then that is applying the load to the specimen and you can have a sensor on the specimen. in this case it is put as a LVDT, LVDT stands for Linear Variable Differential Transformer, it is a transducer that measures displacements and give the signals to the controller or data acquisition system and you also have to measure load.

So there is a load cell and the controller and as I told you there has to be a pump which has to give a constant pressure of 21 MPa, so this could be the system for applying some, doing some test on tension or compression, you can have something for testing flexure, it is the same setup which can be used for measuring responses in bending of flexure, you would have beam like this, you can have the load cell attached to the actuator itself, here we had it below but it could be attached to the actuator itself.

Mostly this is the configuration that you would see in the testing machine, you will have the actuator and at the bottom of the actuator or at the top of the actuator you will have the load cell and there you are having the supports at the bottom which are giving the reaction and the load cell and the actuator is moving up-and-down to give you the loading on the beam and we will have some device there for measuring the displacement or stains, we will see in later slides, more examples of how this is done, so this is the entire configuration of what you would have in a testing machine, you have a frame to reacts against, you have the actuator,

actuator is driven by the servovalve, the servovalve is getting oil from the pump and a signal from the controller.

Then the servovalve moves, such that it gives you the loading that you want on the specimen, the specimen on which you have already put some sensor, which is giving the signal to the controller, which is telling the servovalve if it is going fast enough, slow enough or it should stop , so you can have cases where one pump is attached to two machines also, you can have the pump shared between different systems like we have shown in the above diagram.

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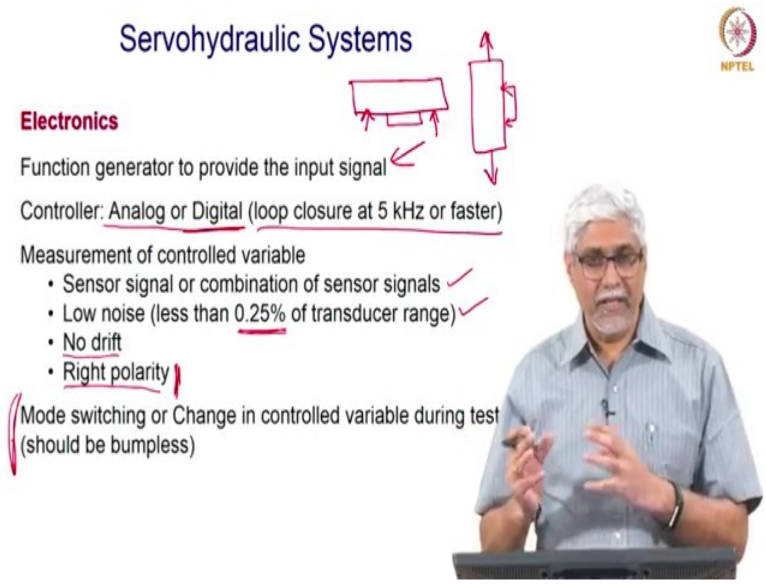

Going back to the electronics, the electronics has a function generator which is defined by the user, we tell the function generator whether some variables should increase constantly, at what rate it should increase, if it increases it should stop and come down or go up, it should not change the rate as it goes during the test, so that is what the function generator is doing. The controller could be analog or digital, now mostly they are digital very rarely may be in old systems you will find analog controllers, mostly these are digital controllers like based on a computer, which are closing the loop at about 5 kHz or faster, that means 5000 times a second, the error is being calculated, so you can imagine how fast this is happening.

So it is much faster than what an operator could do, sometimes we find in some labs where the operator is trying to change the control such that you get the velocity or the machine stops or not, this system acts as 5000 times a second which obviously no human being can beat, so that is why the system is able to react so fast and give us the signal that we want or the response that we want, we generally should have a sensor giving a signal because we have to measure something to provide feedback, this signal should not have noise, very low noise, generally we say the noise should be less than 0.25% of the transducer range, it should not drift, meaning that the zero should not keep on changing by itself, it should be stable and it should have the right polarity, which is very important and what does this mean? That it should tell the machine whether the actuator should move in one direction or the other.

The machine may not know if you are doing a tension test or compression test or a bending test, for it, it has to react in a certain way and you can imagine that if you have a specimen, that is undergoing compressive load, the transducer will close, so you can tell the machine if the transducer closes that means that I am applying compressive load, if instead of compression on the same thing, I apply tension, then the transducer opens, so you have to give the right polarity so that the specimen is stretching and that means, the test, the system knows that its applying a tension.

But what happens when you have bending? when you have bending and say you have a transducer below, when you are applying load, almost like in compression, you find that the bottom is stretching which is similar to what you saw in tensile test, so if we do not tell the machine that the polarity is different, it will react the wrong way and break the specimen, so here you have to tell that, when the actuator is going down there is tension at the bottom and this is something that the machine does not know unless you tell it, and the way you tell it is by changing the polarity, so a lot of time I have seen test where the specimen is putting at just breaks when you start the machine because the polarity is wrong , so it is very important that the machine knows which direction it should move to give you the loading that you want, otherwise it could go the wrong way, so that is polarity.

Also what is important and which is available in modern machines, which were used to be very difficult to do in older system is mode switching, that is you start with one control and without any bump or a drastic change in the load it should be changing to another control, for example I start the test in load control and then switched to displacement control because load is easier to apply, displacement depends on the reaction and later on I’ll show you that it can change from one type of displacement to the other also, so it should facilitate what we call mode switching or change in the controlled variable, controlled variable is again something that I want to monitor, I wanted to go in a certain way that is the controlled variable.

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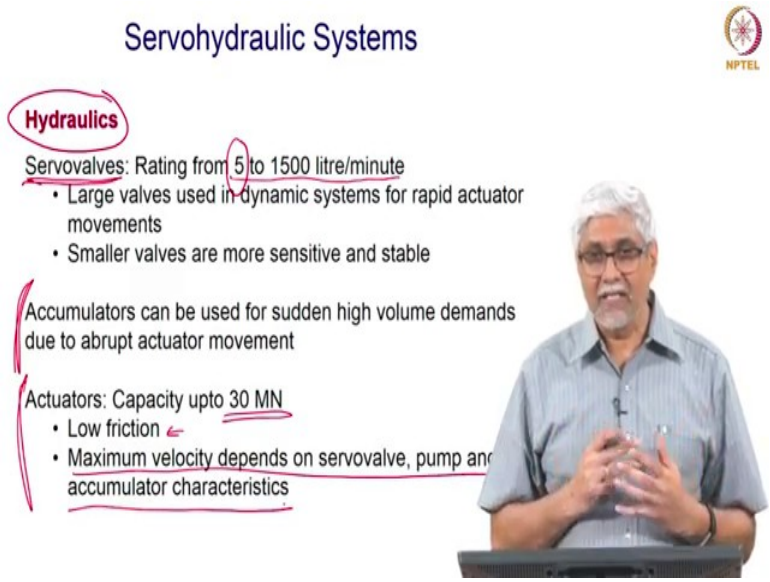

To provide all this we need good hydraulics, we need the servovalve that I told you is like the brain of the testing machine and it can range from 5 litres to 1500 litres per minute, what does this mean? This means that so much of all can go through it in a minute, the larger servovalves can make the machine go very fast and slow, the smaller ones are very sensitive, so if you have low loads and very slow test and you have a system which can break very easily you will go for a smaller servovalve, so it is not always good to go for a very large servovalve, you will not have sensitive control and the machine will not be able to apply small loads, small displacements , so the servovalve has to be sized accordingly depending on what test you want and larger servovalve are also more expensive.

Along with the servovalve we have something called an accumulators, accumulator can provide lot of oil in a sudden burst, it is basically like a cylinder which has oil under pressure and when oil is needed because of a sudden movement the oil comes out of the accumulator, so you will always see in a testing machine that there will be in accumulator, these are like small tanks, cylindrical tanks which have oil under pressure.

Then of course the actuator, the actuator is what is actually applying load and there are actuators which can go up to 30 MN or even higher, these should not have a lot of friction because you can imagine that if the actuator has friction, it is not really transferring the load that you want, and not moving fast enough. The velocity depends on all these, the servovalve, the pump and the accumulator, how fast or how slow the piston can move, how fast can you do test, what is the highest frequency of test that you can do, so when you are buying a system you should ask the supplier to give a displacement frequency curve, how fast the displacement can be applied, how fast the load can be applied, so that you know how fast the system can react.

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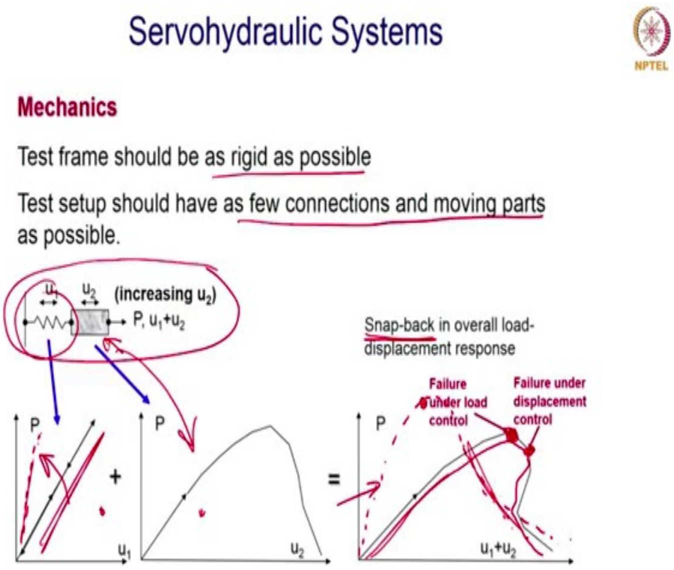

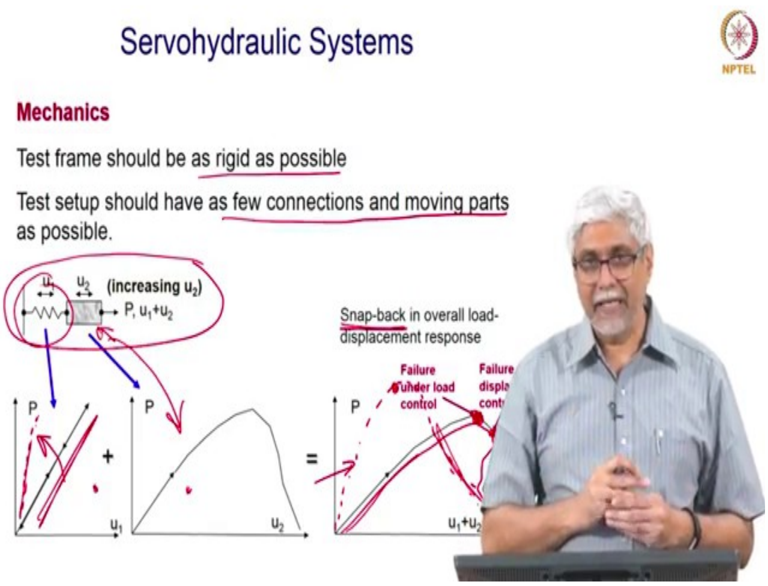

So we have looked at the different components of the servohydraulic systems and let us also tried to understand the mechanics of what is happening in a test so that we can choose the right configuration as much as possible. So little bit about the mechanics, the testing frame or what the actuators reacting against and what the specimen is reacting against should be as rigid as possible, it should be like having as few connections and moving parts because all this decreases the stiffness or the rigidity, we want something to be as infinitely rigid as possible and that we can explain by looking at the simple diagram in above image, where the specimen and the actual behaviour of the specimen is plotted and along with the specimen everything else is also deforming, the plate on which load is being applied and whatever fixtures you have also are deforming, even the actuator is deforming a little bit .

That is represented by the elastic response, we would like the actuator to be as stiff as possible why? Because the sum of the two is what we see in above image or what the machine sees there, so if you have something very flexible, you could have the sum such that it goes up reaches a peak and then it actually comes , that is called Snapback.

If this was more rigid, then you would have a different system as shown in above image , you would have a system that is stiffer, you will not have this snapback occurring, it will come down in a gradually progressive manner so with displacement control we will be able to get the whole curve, if you have a curve of rigid, imagine you are doing load control, load control is where you are telling the testing machine keep increasing the load in a certain rate or keep the load, that is load control.

We are telling the machine to keep changing load in a certain manner, if the specimen behaves as shown in above image, you would get failure at the peak because beyond that point load cannot increase, the machine will try to increase a lot of load and it will crush the specimen, even in the case of something rigid , we will have the specimen failing at the peak, if you were to do displacement control, displacement stops increasing at a point shown in above image, so you will have failure there, the machine cannot do better than this but if you had a curve that was constantly going down because you had stiffer response here then you will have a smoothly increasing test .

So that is the reason why everything other than your specimen should be as stiff as possible, you should not have long connections, you should not have long rods connecting your actuator with the specimen and if you have a long actuator do not use the whole length of the actuator were to run the test at that the actuator is at the end, if it is not going to displaced too much because the actuator length is also acting like a spray , so these are few things that if we remember, we can have a test been more stable.