Fundamentals of Industrial Oil Hydraulics and Pneumatics

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Module 4
Lecture 16
Proportional Solenoid Pilot Operated Two Stage Pressure Relief Valve (PPoPRV)

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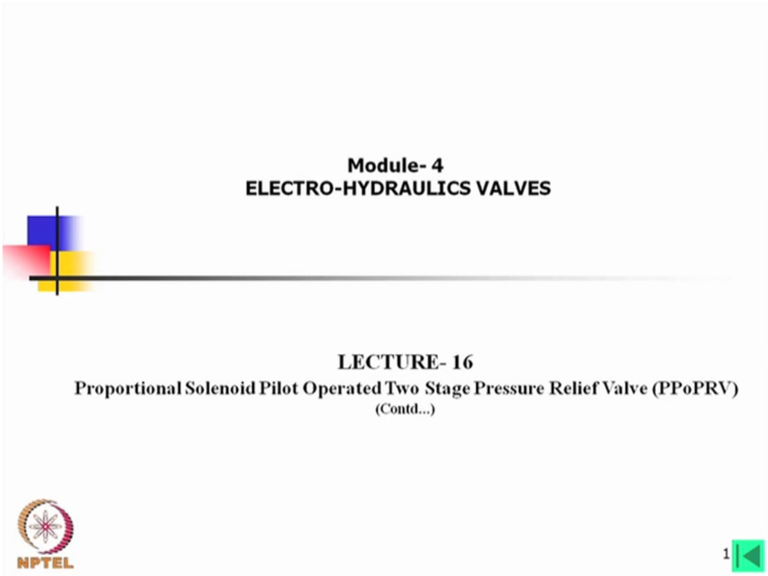

Welcome to today's lecture on Proportional Solenoid Pilot Operated Two Stage Pressure Relief Valve, in short form which is called PPoPRV, P first P for proportional, second P is for pilot, o is for operated and PRV is pressure relief valve, this term is often used for such a valve. However, what we are discussing here this is solenoid operated but it might be other type of drive also there. Now this lecture essentially the continuation of the lecture 15, which we delivered may be last time two weeks back.

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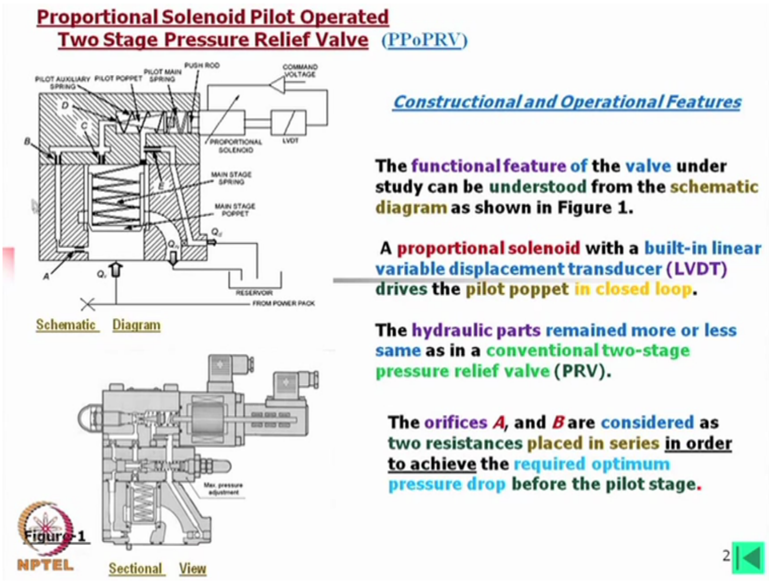

Now, first of all again let me explain what is the valve, so we will again I shall again explain constructional and operational features. Now if I look into the sectional view of this valve, this is again it is a schematic not exact section neither it is photographic view this is may be computer developed. Now here what we find this portion including this portion you can imagine this is an ordinary pressure relief valve, how it operates? This is connected to the system like, so one side pump and other side may be the system.

Now the flow is coming in here, not here do not make a mistake this is going to tank this portion is going to tank and this is the system line. So here it is shown. And then the flow is coming over here and through an orifice here and a constriction here it is going through this passage to this place, okay here is another orifice, this orifice together orifice and constriction together we named as A and then this is B another orifice and then we find the pilot stage so this orifice is D this is variable orifice and this has great role on controlling the pressure.

And then after passing through this orifice the oil which is going through this this variable orifice it is going to the tank, okay and in between that which is not shown here there is another you can say valve block which is basically set the maximum pressure, when we call the proportionate solenoid pressure control valve or pressure relief valve in this case then this is the force on pilot stage can be given by the proportional solenoid in such a way that with the input usually voltage it might be also current input with the voltage the output that means in this case pressure will be proportionally related, usually this operates in 0 to 10 volt and towards the end we would say 8 to 10 volts and towards the beginning 0 to 2 volts, it may not be linear but in between from 2 to 8 volts the pressure relation will be linear.

The advantage of this valve is that you can one can put easily in the control online control. So in fluid power usually such phenomena this orifice flow, then pressure control all such are nonlinear highly nonlinear but there will be nonlinear inside. However, this is designed in such a way that input, output will be linear and which can be computed directly with due to the linear relations practically no time and due to this reason these valves are used with the modern control units or sophisticated control units, although performance may not be very close to the servo valves, servo valve is having better performance. Considering a servo valve of better equivalent size if we say that is performing with 100 percents the proportional solenoid will perform in between something 95 to 98 percent of the desired output, right.

Now this I have just explained or stated how it is performing but if you look into the performance how it works that through this orifice this passage is connected and let us consider this is closed, then what is happening the oil is creating a pressure on this main spool which is supported by spring but this force is not enough to open this one. So flow is being used for the system.

Now suppose there is increase in pressure say I would start like this the functional feature of the valve under study can be understood from the schematic diagram and this oil is connected to here, this means that as long as there is no flow pressure here and pressure here is constant. As well as through this orifice C, this orifice has no function with the flow main but this has a function with the damping of this main spool it is required when the transient due to this orifice it damp and somewhat the motion of this and it becomes more stable, if you remove this orifice C, still this will work but there will be more vibration than the valve with this orifice.

Anyway, the everywhere pressure remains same, so this side of the main spool total force definitely will be more than this so this will remain closed. Now when the pressure increases then due to the thrust it is already set we have given a force here, okay we have given a force through the voltage there is a proportional solenoid through this end of the spool we can say here. So this is giving a force in this directions, so it is being closed and it remained closed.

Now with the pressure here when this pressure increases the force increases then what will happen? This will be compressed and this is the main spring here, this is the main spring and this spring is an auxiliary spring just to keep this is poppet in position pilot poppet is position, this has practically no function over the force, whereas this spring is transferring the force from this to this, you may ask why it is not direct it can be shown that if we fix this is direct then it is very difficult to get this proportional characteristics.

Anyway, so what happens? This opens and once this opens the flow begins from here to here to this drain, okay. So there is a separate drain connection for this passage it also can be connected to the main passage however, here the separate passage function wise it is more or less same. Now once the flow begins then definitely there will be pressure drop through this passage.

Now with this dropped pressure here but look at this flow is through this passage not through this passage yet. So whatever pressure here the same pressure will be there, so but that pressure is less than this pressure so at one point this pressure force plus spring force totally will be less than whatever force is generated here. So what will happen this will open and the main flow will go to the reservoir.

Now this situation will be maintained unless this pressure is not below the whatever force we have given here, whatever for what pressure we have given this input, okay. Now the question is that we could have make it as direct, direct proportional valve is also available instead of pilot stage it is operating this one, what is the advantage of this? The advantage of this as I told earlier due to this pressure drops here through the different orifices this remains stable for longer period.

Why we need such stability? Look at this if once the flow begins from here then here is the tank pressure, tank pressure is almost 0, 0 pressure or may be slight pressure for the filter and other things, whereas here pressure is high pressure the system pressure. Then once the flow begins then definitely there will be pressure drop as well as here will be also pressure drop. By using so many orifices what happens that here the orifice opening is very much controlled so that maintaining the pressure almost equal to the system pressure the flow the whole flow is diverted to the tank, this is a large orifice as (())(12:17) this is also very well orifice but this is a large orifice, okay.

So this is basically the operations now I have shown you that by the equations how the pressure is being dropped, what the force everything a part of that, today I shall discuss the rest of the portions.

Now here again if you look into this here there is a close loop feedback, here we are having a LVDT that is that controls the armature positions for an input this is not close loop for the whole system, this is close loop only for the proportional solenoid which is displacement of this solenoid is recorded by LVDT and through this it maintains the position with force to generate a particular force in these directions, okay.

Now this hydraulic parts the advantage of proportional solenoid valve is that, this other hydraulic parts including this one, this is the maximum pressure set again I would say suppose this is working say at 10 voltage let us consider maximum pressure can be controlled is 10 Mega Pascal so (())(13:46) to say at 8 voltage because 8 to 10 that may not be linear at 8 volt say 10 Mega Pascals or let us consider 8 Mega Pascals.

Then this valve here the setting will be slightly higher than that, so that if pressure increases above that then this portion will not work this directly it the flow will continue like this which including this an ordinary valve, this is an ordinary valve. So this is additional safety feature. However, this valve can work without this one also until there is say something wrong with the voltage input or other, otherwise it will work.

Suppose if the pressure increases upto 12 voltage still this will generate only the force for 10 Mega Pascals and this flow will be there but with this there will be no chance of damage at these portions, so that is why this portion is additionally introduced there. Now so orifice A and B are considered as the two resistances placed in series in order to achieve the required optimum pressure drop before the pilot stage.

If we replace we have done of our own experiments and we have seen if we replace one then performance is no longer linear, neither the stability is available there. So these are designed in considering the linearity as well as proper function.

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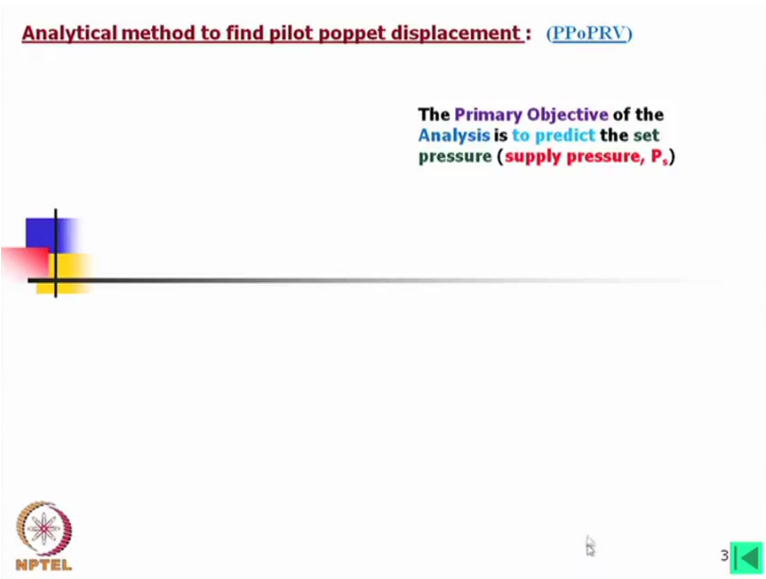

Now what we did that instead of that block there we put another block just manifold you can say so with the hole passage hole and keeping the passage hole intact but this facilated us to put the connect this on pressure gauge here to measure the pressure here, another pressure gauge here to measure the pressure here, another pressure gauge or transducer to measure the pressure here and another to measure the pressure here and another one to measure the pressure inside this pilot stage.

However, we did not have much scope of measuring the pressure at these two points very closely, what we consider whatever pressure is there the same pressure is here as well as whatever pressure we are measuring here the same pressure is inside that roughly why roughly it is almost giving the pressure drop within this variable orifice, may be slight error is there but it was very close to that. So our arrangement was like this to measure pressure at different points.

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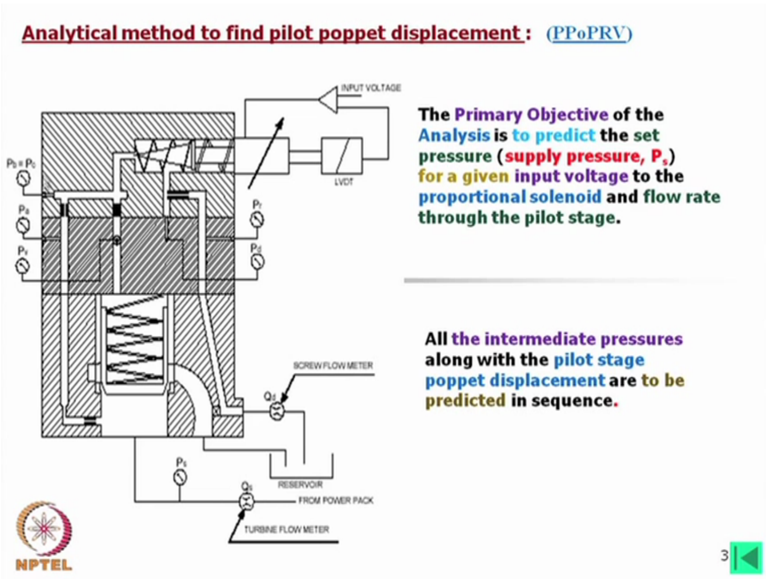

Now the primary objective of the analysis is to predict the set pressure supply pressure. So what we wanted to do, we wanted to study the steady state characteristics. So for the steady state characteristics if I know if we know the proportional solenoid feature fully completely then from there if we know the orifice area, everything can be calculated and we can develop the design procedure of such a valve.

However, it was very difficult to know the real solenoid characteristics neither it was possible to test it separately because it was a integral part. So what we did by some trial and error we first found out what might be the force what are the forces generated by the armature solenoid armature at different voltage, for that what we could do we measured the different orifice area, we could measure the spring stiffness, we could measure the dimension of the poppets, dimensions of the solenoids, angle etc.

These data is available with the manufacturer but the problem is that they will not provide us the data. So we took one valve and we measure all such parameters and then we try to establish the design procedures particular to examine the steady state performance and also we examined if we change the orifice what orifice dimensions, then what will be the changes in the performance and the valve.

Then for a given input voltage to the proportional solenoid the flow rate though the pilot stage that measurement we did. So what we did while the oil in between these passages we put a flow meter like this just to measure the flow through the pilot stage. All the intermediate pressures along with the pilot stage was measured by placing the transducer at different places.

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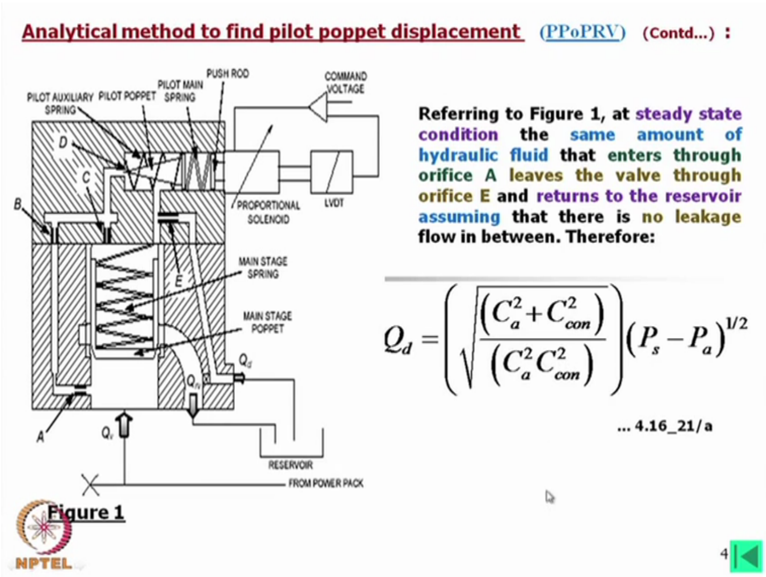

At steady state condition same amount of hydraulic fluid that enters though orifice A will pass though orifice E. So using the orifice equations we can write down the equations because we know the pressure at different positions so we can write down the equations for the flow and we can easily knowing the flow rate we can easily calculate the how much drop at different places even say for that purpose if we know the dimension of the orifices even we can calculate what is the coefficient of discharge at different points.

Now the flow equations that means we are now considering the flow from here to this, to this, to this path and here. So first of all first we consider the flow through this path Q d we have measured and then we can write down this equations, this is root under the pressure differentiate this pressure we have measured, not here we have measured the pressure here because the dimension of this constriction could not be measured.

However, there should a Rho term this Rho term is included within this term, what we have consider C a is a coefficient, not coefficient of discharge this as I told including this Rho figure, this is a coefficient this coefficient is for this orifice and this coefficient is for this orifice. These two restriction say like a spring resistance in a series so as you know for that purpose we can write down the equation in this way, so we develop these equations.

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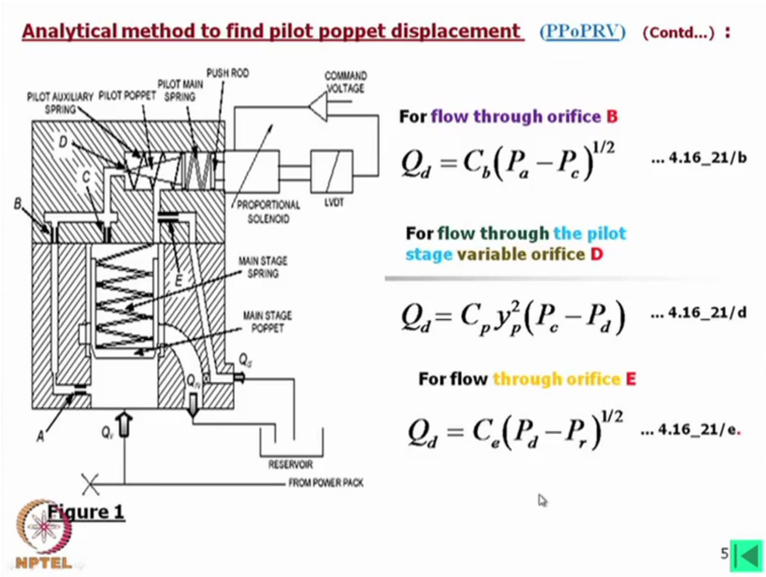

But this flow again equal to flow through B, so we can write down this equation the C b also includes that Rho value I will show that how it is included. Then through the orifice D we can this is the variable orifice, this equation definitely will be different, where y p is the displacement of this poppet, okay C p is again the coefficient of discharge and Rho part and P c, P d is the pressure difference between these two points. So we have written in this term but this can be detailed analysis considering the area etc I will show that area is also there included.

Now flow through E also we can write like this, now here I would like to mention that orifice A and B like the is we say this orifice is normally we think this is a very thin plate, plate sort of things through which there is a hole. Now orifice may be a straight hole or orifice usually may be in the a convergent towards the downstream, okay. What we saw these two are of that type is it convergent in the downstream, okay and this diameter is very small 0$5 or less, okay.

However, this orifice was slightly longer this E is a small hole diameter is more or less same is slightly higher than this but this was a long one, but as we know that for such a small orifice hence such a long orifice knowing the diameter of the hole and length ratio we can use different formula like this. However, here still this formula can be used if we can properly evaluate that (C) C e.

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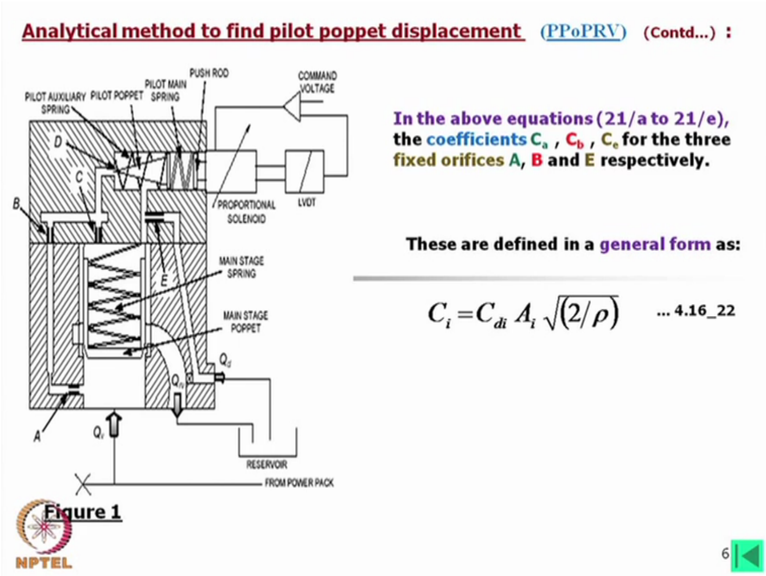

Now in all these above equations these four equations I have shown C a, C b and C e for the three fixed orifices A, B and E respectively. These are defined in a general form as C i is equal to C di A i root over 2 by Rho, so this coefficient includes the coefficient of discharge, area of the orifice this is the nominal area I would say nominal area in a say we directly we can write this A i is equal to the Pi d square by 4, where d is the diameter of the hole without considering its (())(24:53). Now I is A, B, E etc for respective orifices.

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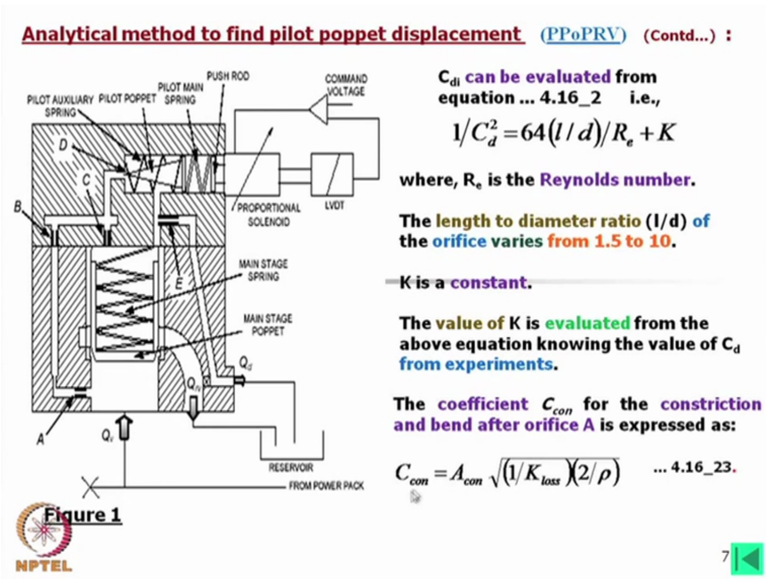

Now C di can be evaluated from the earlier equations 4$16_2 if you remember the earlier equations I think it will be 4$15 not 16, the earlier lecture. So this is 1 by C d square is equal to 64 l by d where l is the length of the orifice, d is the diameter of the hole and R e the

Reynolds number plus K as a constant, okay. So l by d ratio the orifice varies from 1$5 to 10 normally in this case these two orifices are very close to that, whereas this was slightly higher but not 10, exact dimensions I have not shown here.

K is a constant which can be evaluated from the above equations knowing the value of C d from experiments, if we find out we can find out the C d then this value also can be found out and then for a particular type of orifice perhaps we can develop a anti empirical relations so that we can calculate K anytime. The coefficient C con for the constriction here after orifice A is expressed as with this relations, we put the constriction area here and 1 by K loss we measure simply the loss there and from which we can find out this coefficient, okay.

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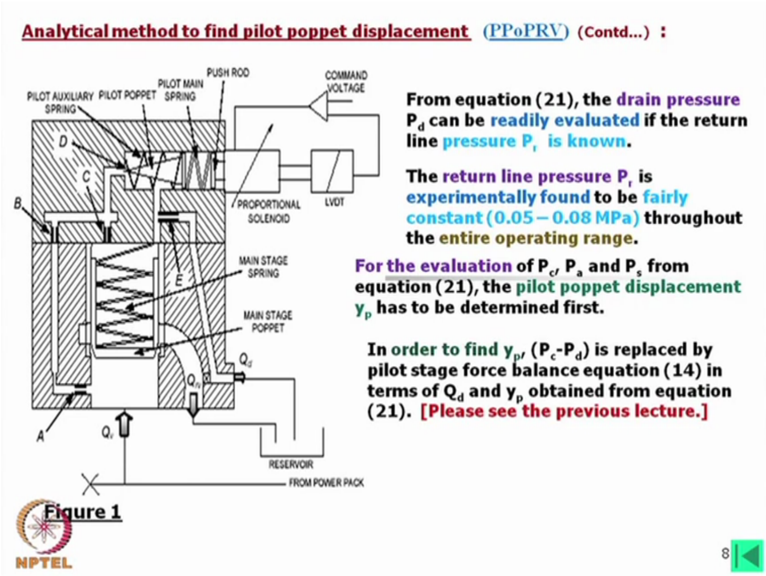

So as we know the pressure drop at different point to measure the loss over here, what we did we remove this one and also we remove the orifice, simply we measure the flow and pressure drop at these two points and then we found out what will be the loss there, okay. Now from equation 21 there drain pressure P d can be readily evaluated in the return line and pressure P r is also known, this pressure also measures so this is known.

So with such the known values we can calculate the initially what we did we evaluated all coefficient of discharge whenever a orifice is put we first evaluated the coefficient of discharge of all such points. Now this P r is not very high it is 0$05 to 0$08 Mega Pascal only that of course depends on how much restriction you have put in the return line if there is one filter only then may be one value, if filter with say cooler is there then it will be more, this depends on the resistance which easily can be measured.

For the evaluation of the P c, P a and P s from equation 21, the pilot poppet displacement has to be determined first. Now you see this first we have measured the pressure and next we have found out the C d and from which we have prepare the set of equations now what can be done with those using those equations again we can P c, P a, P s all we can P s is known value all we can calculate with respect to this displacement y p displacement.

Say for example this means that next for the next calculation we need to calculate the y p how much will be the displacement, ultimately we have to put in terms of the displacement all the equations, okay. So in order to find y p that is the poppet pilot poppet spool displacement P c and P d is replaced by the pilot stage force balance equations, so this equation 14 if you remember this 14 equation was used in terms of Q d and y p obtained from the equation 21. So first we calculated C d etc then we from knowing that Q d we calculated y p, I will show these equations.

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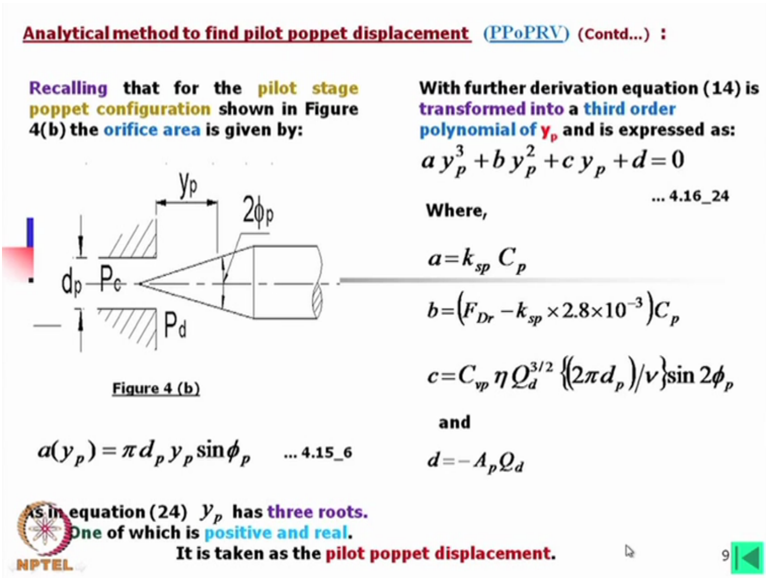

Now we should recall here what is the geometry for this poppet spool or the orifice area, if you remember in the earlier lecture I described that how the flow is occurring here, the flow is coming over here and then this flow is going like this and it is ultimately going to the tank through this orifice E and other leakage passage. Now the we know this angle, okay we know this hole diameter, so area must be this annular passage that which we can calculate from this I mean it is not like that, that we are subtracting this area from this area. Rather we are considering the particular path through which the leakage is going.

So we have taken this component, Pi d p is the peripheral area d p is the diameter of this hole and Phi p is the angle, okay. So we use this equation to estimate the area. Now here another point is that what is the jet angle here, in normal course we can expect jet angle will be Phi p but in real case it is slightly higher than that, that means there is a separation of the flow here.

So flow you can say that it might be slightly higher than this, so actually we should take that angle here but there is no way we can measure this angle, so what we do? We take this angle later we put a correction factor knowing experimentally what is the flow actually occurring there, okay. Then with further derivation equation 14 is transformed into a third order polynomial equation for y p and is expressed as I am not showing the details of these equations from the note you can or if you just go back to the earlier lecture from there you can calculate and ultimately we can put these equation in this form.

This is the third order polynomial equations, where a can be put k sp and C p and b is put within these terms these are coefficients, these are all coefficients where this is the force driving force and c is C vp then Eta Q d 3 by 2 2 Pi d p by Rho sin 2 theta p. So these derivations again I am not showing here these derivations can be obtained once we exercise these equations then automatically this terms will come and we shall put in this form and d is equal to minus A p into Q d, A p is the area of this I mean this hole, not this orifice here, A p is the this hole diameter, which is a known factor, Q d is also known.

Now as in equation y p equation 24 clearly there will be three roots. One of that will be positive and real and which can be considered as pilot poppet displacement, okay. So if we solve these equations then we will have three values one of that which is positive and real we will consider that value for the poppet displacement, okay.

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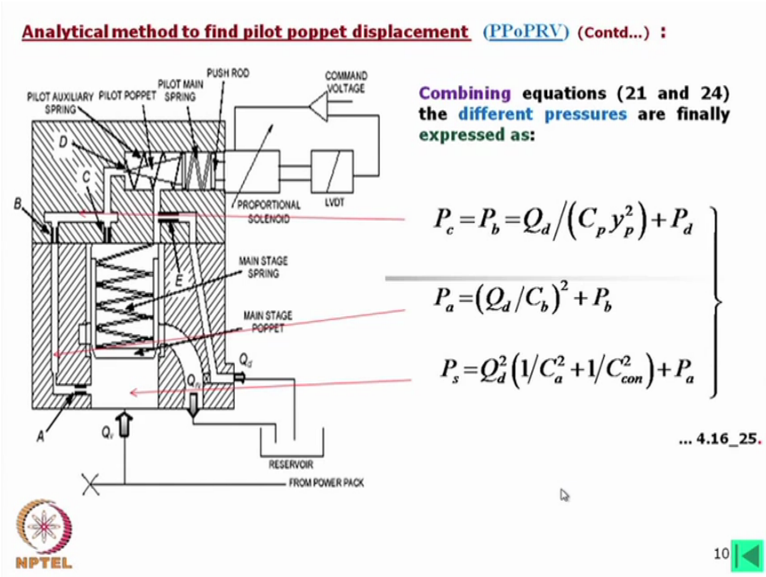

So combining equations 21 to 24 the different pressures are finally expressed as this P c the pressure here is equal to P b that means P c and P b this zone pressure is derived by Q d is the drain flow divided by C p y p square plus P d, okay. Then C p we have evaluated earlier lecture y p we are calculating from these equations solutions and then clearly we can calculate the pressure there.

And P a is Q d by C b square plus P b and P s is Q d square by 1 by C square plus 1 by C con square plus P a these all equations are written from the earlier we wrote the equations and this just we have written this equation in terms of pressure. So this easily can be evaluated.

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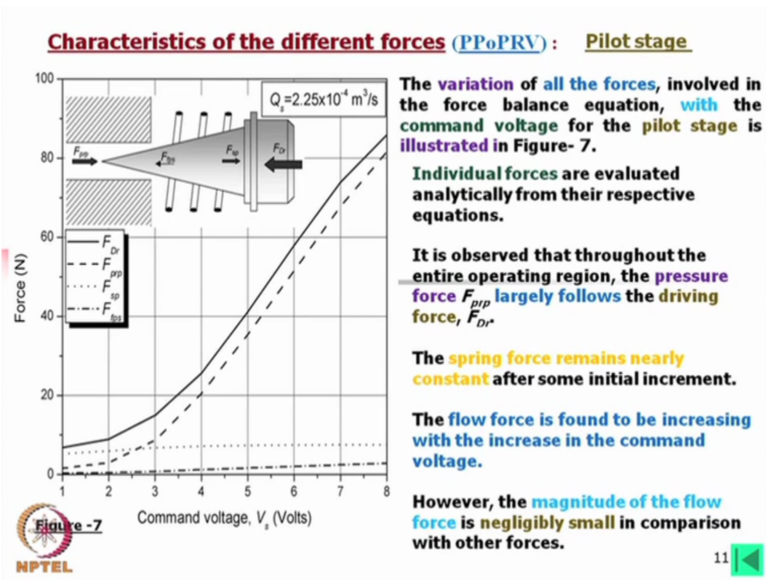

And after that the variation of all the forces, involved in the force balance equations, with the common voltage for the pilot stage illustrated here which we can derive, okay. These force equations earlier we have shown equation 14, this earlier lecture we have shown now here we have plotted. Now if you look into this figure now here system flow is this much, Q s that was the system flow and for that F Dr F, this is F Dr these are different forces F Dr is the force form for solenoid, F sp is the spring force, F ps is the flow force, am I clear F Dr is the force generated by the armature, I mean that solenoid proportional solenoid, F sp is the main spring force not this one there is a spring this side, this is not the main spring, main spring is here so that force, okay and then F ps is the flow force here and F prp is the force generated by the pressure here, okay. So these are plotted, so this will be the nature of the forces here.

Now individual forces are evaluated analytically from their respective equations, this which we have done earlier. It is observed that throughout the entire operating region, the pressure force F prp largely follows the driving force F Dr this is the driving force, okay. The spring force remains nearly constant in between the spring force after some initial increment, okay. So this means that at the say for example when the valve is being operated may be the voltage input 4 to 7 or 8 rather here the linear portion is 2 to 8 for this valve, so for voltage input from 2 to 8 what we will find this spring almost acting as a solid bar and the armature force is being balanced by the pressure force and flow force. Again I will repeat that why we need that spring, if we give that force directly by this spool there will be nonlinearity, this nonlinearity will be reduced if we use a spring in between that.

The flow force is found to be increasing with the increase in common voltage, obviously if the force is increased then what will happen there is much pressure drop with much pressure drop there is the increase in flow rate, so there will be increase in the flow force. However, the magnitude of flow force is negligibly small in comparison with the other forces. This is again that although this force is increasing flow force but still it is less than the other forces.

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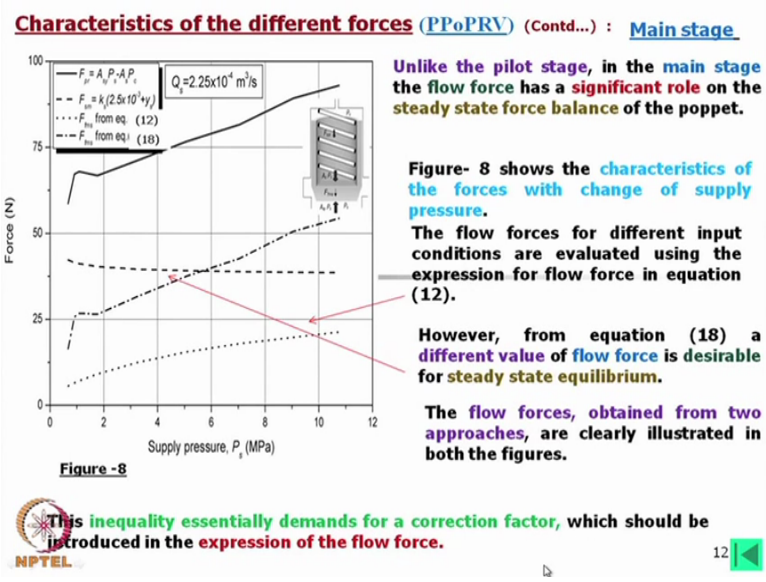

Unlike the pilot stage in the main stage the flow force has a significant role on the steady state force balance of the poppet. Now here what we are showing this is the main poppet we are showing if you recall the valve configurations this is the main flow through which the main flow is going to drain in case of relief, okay.

So in this case the flow force has significant role. The main reason is that quantity of flow is much much higher here and definitely as I told for the balance, for the longer stability this valve is designed this means that this orifice area is very small so that there is enough pressure drop to maintain the system pressure close to this system. Say in case of direct valve what happens once this poppet opens the pressure drops inside then again it close and again it opens so there will be chattering sound but in case of this balanced piston I mean pilot operated valve what is called two stage valve this remains balance for longer time.

So that is why there will be the less orifice area much flow and due to that here will be the high flow forces, okay. Now here the flow force for different input conditions are evaluated using the expression 12, here the expression 12, I am not showing you should compare with the earlier lecture and this is according to the equations 12, whereas the from the equations the other equations there is equation 18 we get a different value, one is one the equations we developed from the general equations, another with respect to the valve in terms of force and other things.

So why this difference is there, definitely as I told we could not consider all the parameter inside, so there will be some differences. Now these differences are observed in all cases who have analysed such valves and therefore we need to revaluate the equations considering a factor for these corrections which we call correction factors.

So the flow forces obtained from two approaches are clearly illustrated in the both the figures earlier figures and this figures also and then the inequality essentially remains for a correction factor, which should be introduced in the expression of flow force, now we will look for that one.

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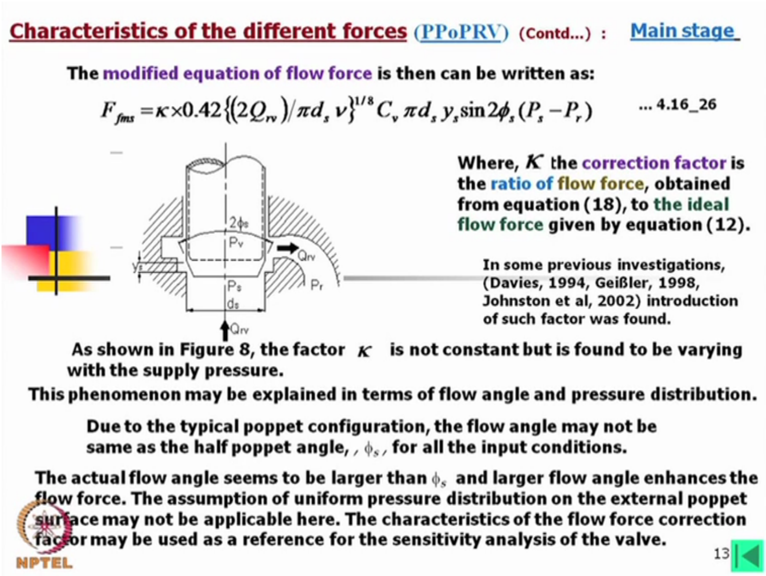

Now the modified equations of flow force is then can be written as with a factor we have this equations again we have rewritten and here we have earlier we have developed these equations without this one, if you remember this equation we developed earlier where we did not have this one, okay. Now we have to calculate this one this cuppa this factor this is the correction factor.

Now where, K the correction factor K or cuppa whatever we call it I think we used cuppa the correction factor is the ratio of flow force obtained from equation 18 to the ideal flow force given by equation 12, 12 gives the ideal flow and 18 gives the obtained flow from these geometries and other things, that means 18 equation without this cuppa was there, okay.

Now in some previous investigations this in the reference earlier reference we have given today I also give the references these say Davies, it is 1994, this is 1998, this is even 2002 they faced similar problem and we also we carried out such analysis in the year of 2004, ya 2004 and this time we when we had to face this problem we found the also faced similar problem but their valve was different. So we had to evaluate this value of our own.

As shown in figure 8, the factor K is not constant but is found to be varying with the supply pressure, this is not the figure 8, the earlier figure 8 this cuppa value is not constant it found to be varying with supply pressure. So measuring the supply pressure we can find out this values.

Now to find out this what first of all we should know what is the angle this poppet angle here. So knowing this poppet angle due to the typical poppet configuration the flow angle may not be same as the half poppet angle for all the input conditions, I mean here again this we wanted to mean that jet angle is not always matching with the Phi s, so due to that this correction factor is required.

The actual flow angles seems to be larger than this geometric angle of the poppet. Large flow enhance the flow force the assumption of uniform pressure distribution on the external poppet surface may not be applicable here. The characteristic of the flow force, correction factor may be used as a reference for the sensitivity analysis of the valve, okay.

So this not only this correction factor from the correction factor again we can examine the sensitivity of the valve, what is sensitivity? That changing the parameter like spring constant and other value what will be the change in the flow or pressure, etc.

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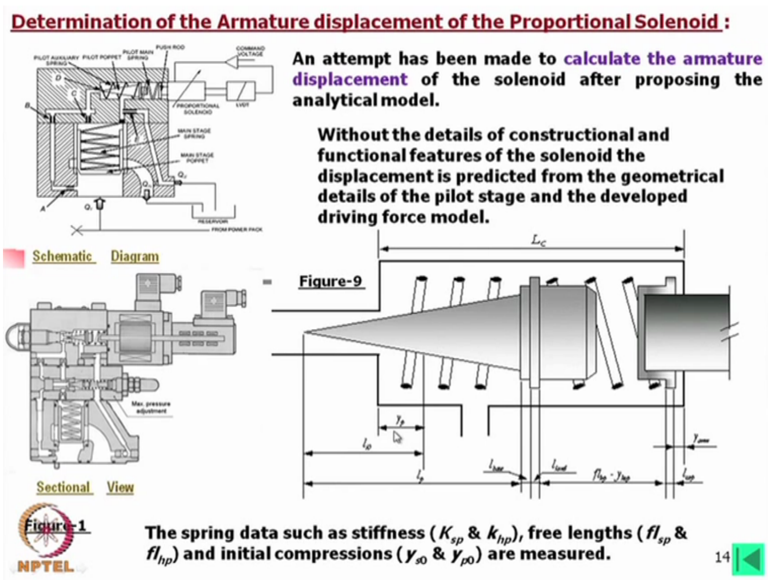

An attempt has been made to calculate the armature displacement. So if we think in terms of design of such valve, so now we need to consider what is the armature displacement. Without the details of the constructional and functional features of the solenoid the displacement is predicated from the geometric details of the pilot stage and the developed driving force model.

You see as I told that it was very difficult to measure the displacement of course if we can calibrate if you could calibrate the LVTD and if you could take the output from LVDT then it could be possible to measure but displacement but whatever the information we already have we have the geometric relation inside, we have the spring stiffness, we have the flow and from there we can find out what we will be the displacement and from that equations definitely it is possible to find out the armature displacement and what we established and with that armature displacement we again re-examined for different pressures setting and we found that result was correct, so we consider that is the armature displacement and ultimately we developed all the equations in terms of armature displacement also.

Now here this first of all to do that what we measure we measure this length, okay. So this is a fixed geometric length and then say this is the say this point is touching over here when it is zero positions, so what we measure the l p we measure from the top to this positions, that means if we measure this distance that is l p when l p was 0, okay. Now this is you can say this is the opening from the orifice point and then this is the position of this (sit) I mean this step and here also this step these two are some fixed dimensions and then this is the dimension for the compressed spring, which the free length f, f is the free length of this spring minus this displacement and here again we had to measure this this capped dimensions because the spring was siting from here to here only, so this dimension we had to include.

And then by equating we were calculating the displacement of the armature so here the critical values are these because what is the compressed length of this spring and to find out this armature length and we had to consider this length also so these are all fixed lengths geometry so this will not vary but once with the force this will vary, this will vary and this will vary, okay.

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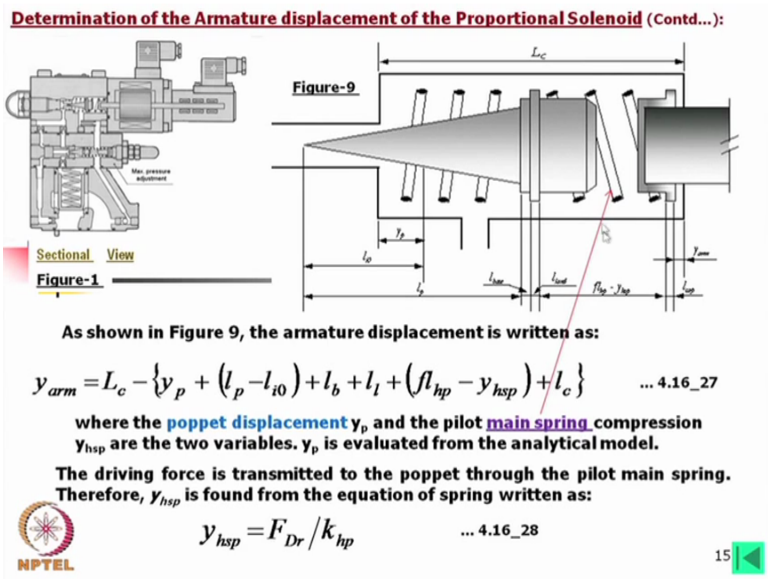

Now next the equation the armature displacement can be written in this form, I am not going into the details knowing these dimensions you can easily find out say this is the l io, this is the l p, okay now it is not exactly matching this I mean because this is written in may be one format, this is other format but these are correspond to this, so l c is here these dimensions, l l is this one, l b is this one, okay.

So you will be able to understand this figure is enlarge I think you cannot read it but there is slightly mismatch. Anyway this is this dimension which can be estimated, this is the fixed, this is also fixed dimensions, this l c also fixed dimensions, this is also we have to measure. Now where the poppet displacement y p and the pilot main spring compression y hsp this one, y p is evaluated from the analytical model, we have already developed.

Now the driving force is transmitted to the poppet through the pilot main spring. Therefore, y hsp is found from the equation of the spring written as y hsp F Dr this is the driving force of the armature divided by K hp is a we can say this spring constant of the main spring.

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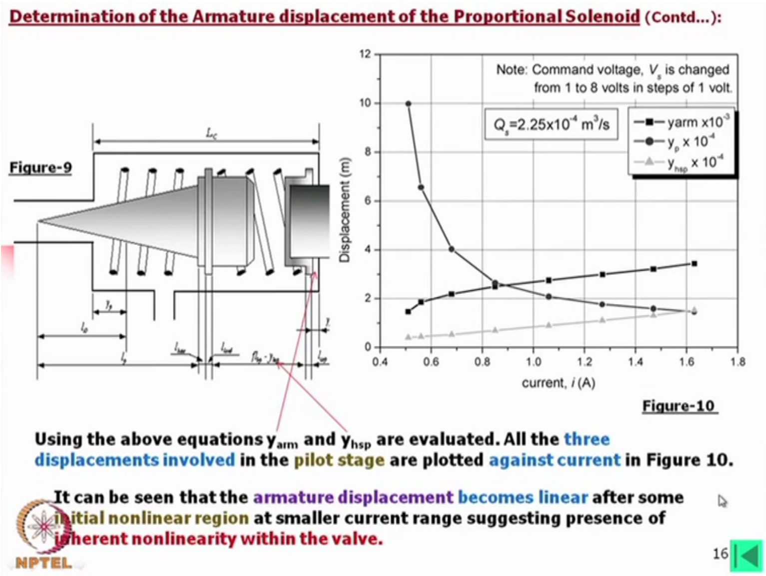

Now this is again you can see are evaluated all three displacement involved this armature, this and this in the pilot stage are plotted against the current. So if we have now plotted these three characteristic. Now this one is the y hsp that is the spring compressed spring length, okay displacement of the spring and y p is the displacement of the main spool and y armature is the displacement of the armature.

Now if we look into study this curve, this is as you can see this linear and this is also we are getting linear, whereas this y p is not linear with the displacement and current, obviously when current is less then displacement will be much higher, this is obvious you see this current is less means the load is less and that load definitely this less pressure drop so there will be more displacement.

It can be seen that the armature displacement becomes linear after some initial nonlinear region, okay at smaller current range suggesting presence of inherent nonlinearity within this valve, you can say this is in terms of current we have written because ultimately in the armature what is fed that is the current, our input is voltage that converted into current and that current relations we find nonlinearities here as well as there will be some nonlinearities here also.

So from this to this you can say linear and this is we normally keep the operating zone from this to this, that means about when the current is 0$7 to 1$6, it corresponds 2 roughly 2 voltage to 8 volts.

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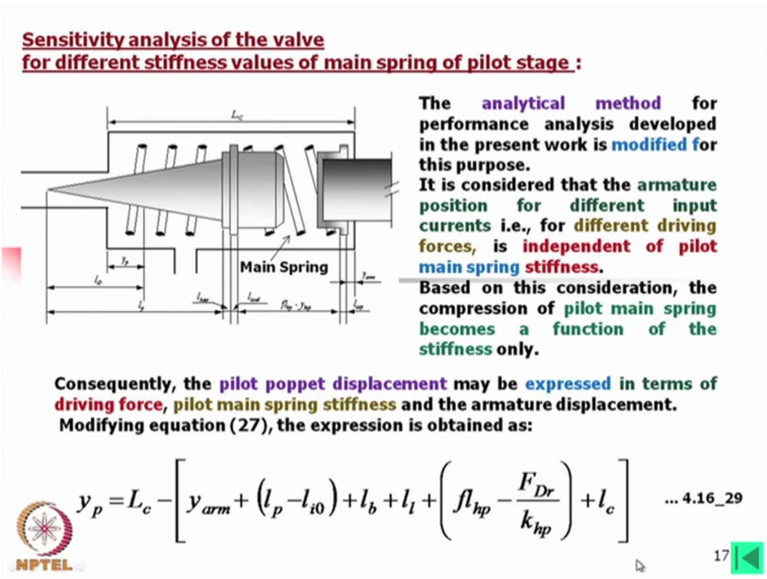

So now as we see this from this point of view we need to modify this our equations for in the usable form and what we find considering that the armature position for different input currents, for different driving force that is for the different driving force is independent of pilot main spring stiffness. So definitely we can examine if we change the spring stiffness what will happen, definitely the range of voltage might be it will change but performance may not change very much. As I told after an initial compression this spring almost acts as a solid valve.

Consequently the pilot poppet displacement may be expressed in terms of driving force, pilot main spring stiffness and the armature displacement. So modifying equation 27 now the expression we can write in this form. Here directly we have the spring stiffness which we have measured and the force also we can estimate from our input voltage and others and we can calculate. So with this we have this this part we have replaced this one we have replaced by this force, okay. So now y p can be calculated.

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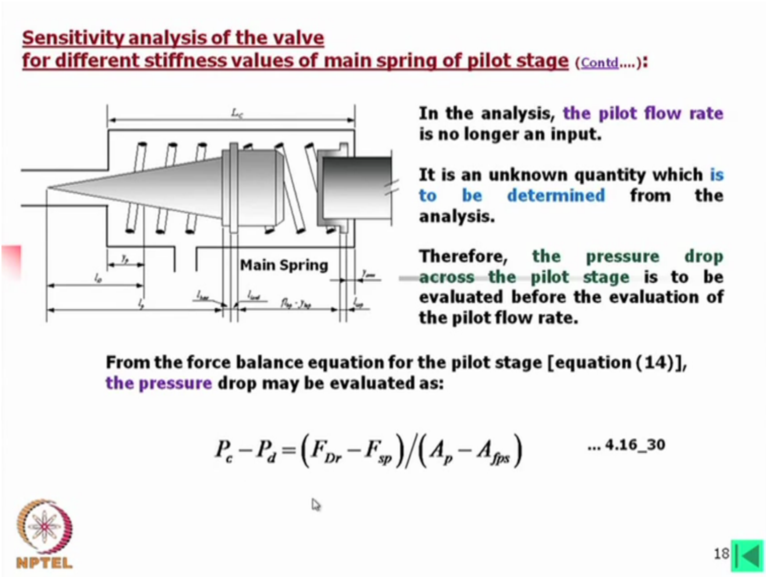

And in the analysis the pilot flow rate is no longer an input it is not an input our input is the voltage we can say. It is an unknown quantity and is to be determined from the analysis, say in fact y p now we have to estimate for the estimate the performance. The presence drop across the pilot stage is to be evaluated before the evaluation of the pilot flow rate, from the force balance equations for the pilot stage the pressure drop may be evaluated as now we can write down these equations, this A p is this orifice area, A fs is this ring area and we can calculate P c minus P d knowing these two force.

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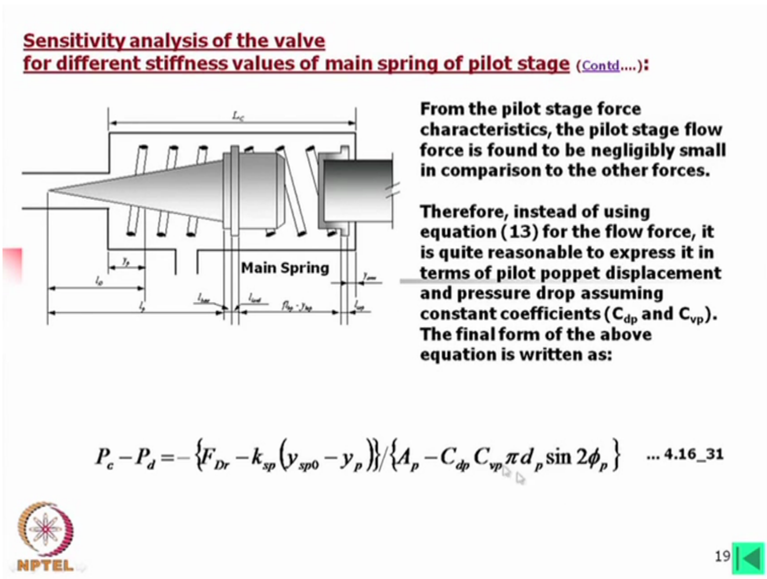

So now we have to finish very quickly so I would like to say from the pilot stage force characteristics, the pilot stage flow force is found to be negligibly small in comparison to the other forces. Instead of using equation 3, for the flow force it is quite reasonable to express it in terms of pilot poppet displacement and pressure drop assuming constant coefficient C dp and C vp, the final form of the above equation now written in this form, whereas this C dp and C vp is the two coefficient of discharge at these points. So these are separately evaluated and we can now write down these equations.

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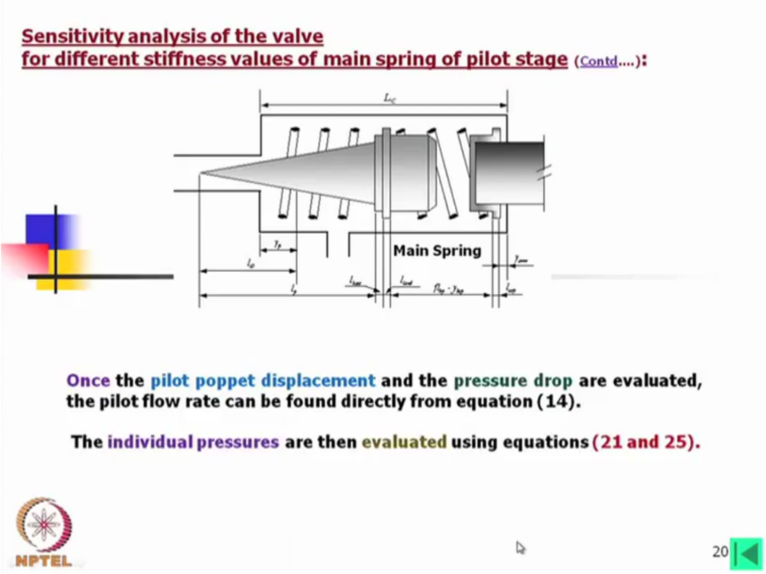

Once the pilot poppet displacement and the pressure drop are evaluated, the pilot flow rate can be found directly from equation 14. The individual pressure are then evaluated using the equation 21 to 25.

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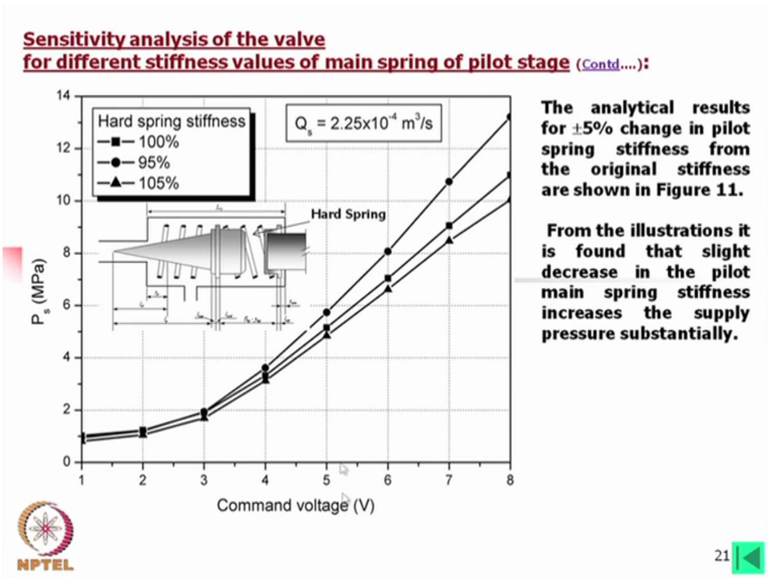

And here we have seen the three different plot, okay. The analytical results what we have done actually we have estimated what will be the sensitivity, the analytical results is plus minus 5 percent change in the pilot spring stiffness, this is purely theoretical analysis what we have developed with that why we have shown here you can see the change in pressure and this common voltage, this is 100 percent means the original spring and if we increase this stiffness by 5 percent than it is the this one and if we reduce this stiffness by this one we will get this is the curve this means that by simply changing this spring we will have different pressure range for different voltage but the nature of curve is more or less same.

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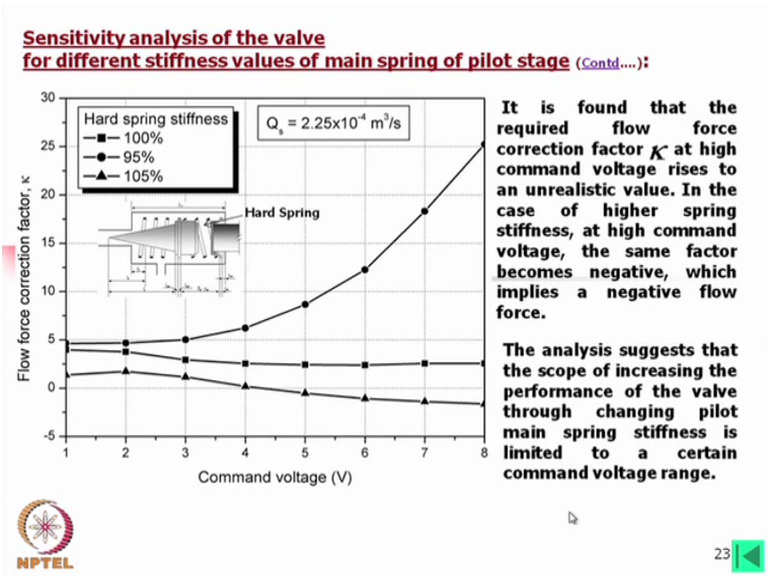

Let us examine the other also that what will be the changes in Q d what we find here for the our original spring, this is more or less constant, linear, whereas due to these two changes what we find it is becoming highly nonlinear, okay. So and also if we look into the flow force correction factor we find that these two are also different from the linearity and then obviously if we want to use say for example this is 5 percent less we have to very careful probably this design will not be feasible, whereas by increasing this spring stiffness the 5 percent we can still use this.

So this is with this I would say that I wanted to show that how a proportional valve can be analysed for its steady state performance, we have not yet shown what is the transient performance, okay.

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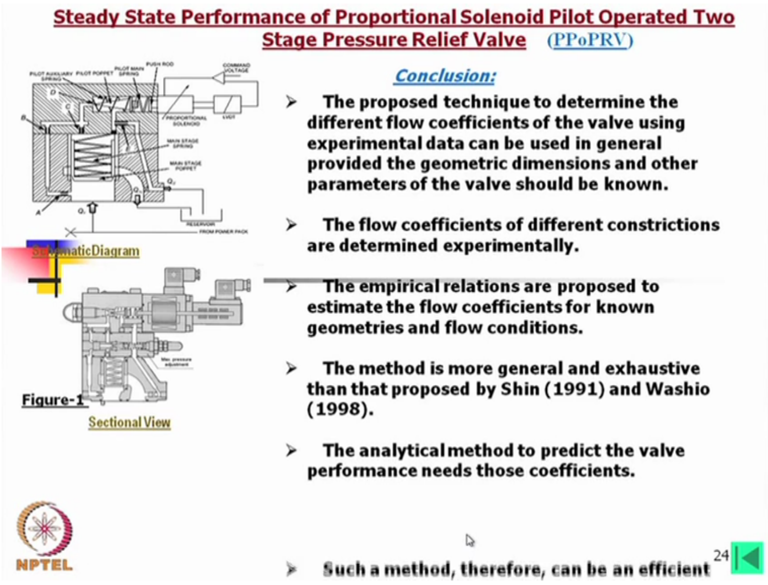

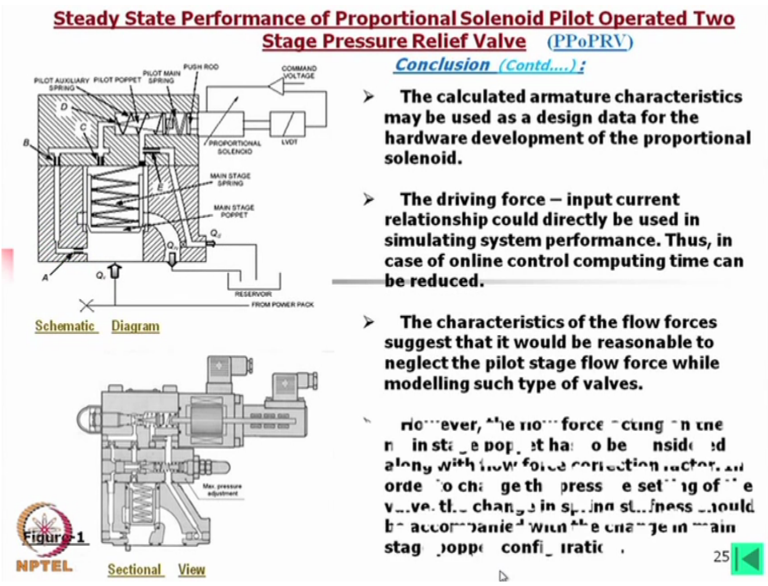

Now I think you can understand from the self-study and there of course the conclusion part which I am not going in details because you have to read it but I have discussed throughout these presentations what might be the conclusions.

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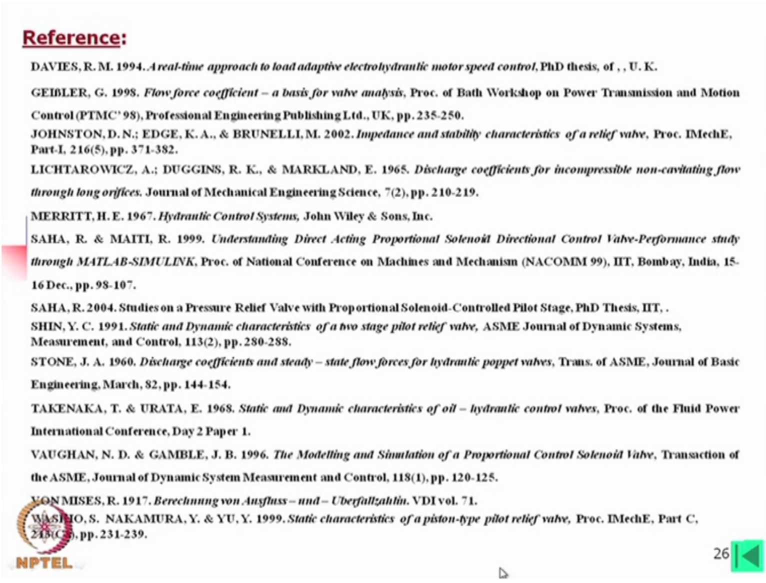

Reference:

DAVIES, R. M. 1994. *A real-time approach to load adaptive electrohydraulic motor speed control*, PhD thesis, of , , U. K.

GEIßLER, G. 1998. *Flow force coefficient – a basis for valve analysis*, Proc. of Bath Workshop on Power Transmission and Motion Control (PTMC' 98), Professional Engineering Publishing Ltd., UK, pp. 235-250.

JOHNSTON, D. N.; EDGE, K. A., & BRUNELLI, M. 2002. *Impedance and stability characteristics of a relief valve*, Proc. IMechE, Part-I, 216(5), pp. 371-382.

LICHTAROWICZ, A.; DUGGINS, R. K., & MARKLAND, E. 1965. *Discharge coefficients for incompressible non-cavitating flow through long orifices*. Journal of Mechanical Engineering Science, 7(2), pp. 210-219.

MERRITT, H. E. 1967. *Hydraulic Control Systems*, John Wiley & Sons, Inc.

SAHA, R. & MAITI, R. 1999. *Understanding Direct Acting Proportional Solenoid Directional Control Valve-Performance study through MATLAB-SIMULINK*, Proc. of National Conference on Machines and Mechanism (NACOMM 99), IIT, Bombay, India, 15-16 Dec., pp. 98-107.

SAHA, R. 2004. Studies on a Pressure Relief Valve with Proportional Solenoid-Controlled Pilot Stage, PhD Thesis, IIT, .

SHIN, Y. C. 1991. *Static and Dynamic characteristics of a two stage pilot relief valve*, ASME Journal of Dynamic Systems, Measurement, and Control, 113(2), pp. 280-288.

STONE, J. A. 1960. *Discharge coefficients and steady – state flow forces for hydraulic poppet valves*, Trans. of ASME, Journal of Basic Engineering, March, 82, pp. 144-154.

TAKENAKA, T. & URATA, E. 1968. *Static and Dynamic characteristics of oil – hydraulic control valves*, Proc. of the Fluid Power International Conference, Day 2 Paper 1.

VAUGHAN, N. D. & GAMBLE, J. B. 1996. *The Modelling and Simulation of a Proportional Control Solenoid Valve*, Transaction of the ASME, Journal of Dynamic System Measurement and Control, 118(1), pp. 120-125.

VON MISES, R. 1917. *Berechnung von Ausfluss – und – Uberfallzahlin*. VDI vol. 71.

WASHIO, S. NAKAMURA, Y. & YU, Y. 1999. *Static characteristics of a piston-type pilot relief valve*, Proc. IMechE, Part C, [illegible], pp. 231-239.

And finally these are the these are the main source from where we have developed I have developed these lectures including our own research and thank you for listening.