Fundamentals of Industrial Oil Hydraulics and Pneumatics
By Professor R. Maiti
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur
Lecture 37
Analysis of Three - Way (Spool and Flapper Nozzle Valve)

Welcome to today's lecture, this is an analysis of three-way Spool and flapper nozzle valves. This means that we shall consider three-way Spool valve as well as three-way flapper nozzle valves. In last lectures, we have already learned about the 4 way critical center valve, we have learned general design analysis of 4 way valves which is mostly applicable for servo valves.

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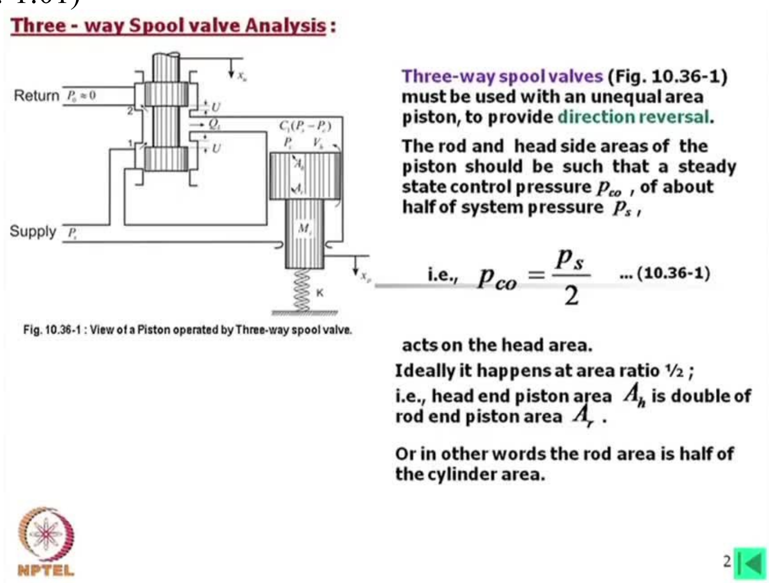

Now the figure 10.361, this is figure 1. It shows the three-way Spool valve and this must be used with an unequal area piston to provide directional reversal. Now what is three-way valve? We know that what is 4 way valve but a 4 way valve normally which are used for the motion control, that is we can control the velocity, we control the position, we control also pressure there, in that case, normally the direction reversal are not frequent.

Or in other words, although direction reversal is done, it is its the scope is there because it is 4 way valve but it is usually started to a rotary actuators and normally we do not go for reversals frequently. On the other hand, if we would like to go for a reversal, in that case, three-way with the load cylinder, this arrangement is the best. Now again, this valve maybe critical center or maybe a open center.

Closed Center valves means overlap valve, are not desired because of the longer bandwidth at the middle. However, critical center valves are mostly preferred, although in true sense it is very difficult to maintain that condition, that critical valve, critical center valve position. Usually, it requires frequent null adjustment null adjustment. However, we shall discuss about that, I will look into the critical center three-way valve.

Now how it is working? If we look into this, this is the supply. Now once the, instead of 4 way valve, in case of 3 valve, supply is one to the valve, one end and other end directly to the rod end side of the pistons. So if we keep this is closed, then this will simply move upward directions. Now let us consider, if we keep it open then in that case, what will happen? The flow is going like this and the flow is also coming in this way and if you think of the regenerative principle and you will find that this will move in this directions and as well as some flow is going out. This is for the control purpose. This is the in servo valve, it always happens.

Now the rod and head side, we call this is head side and this is rod side okay. Now if we look into this, this area is designated by AH and this area is designated by AR. Now the rod and head side areas of the piston should be such that a study state control pressure, PCO is the control pressure of about half of the system pressure PS. Now this PCO or simply PC we need half of that for the better control.

This means that we can express this control pressure is equal to the PS, that is the system pressure by 2, that is desired. Now for that, what you do? Ideally, it happens at area ratio half. What does it mean? That the head area of piston, AH is double the rod end area AR. That means here the AR is the area is the angular area. The head area means the full area. So full area should be double of that angular area.

That can be done, there is no difficult to do such things but you should not confuse here that this does not mean the area, sorry the diameter of the rod is half of the piston area. It is not. The area is half. You have to keep in mind. So usually you will find that what usually you will find that this is also looking very thick because this is more than half of that I mean this diameter is more than half of the piston area.

Anyway this area ratio is maintained half ideally. Or in other words, the rod area is half of the cylinder area.

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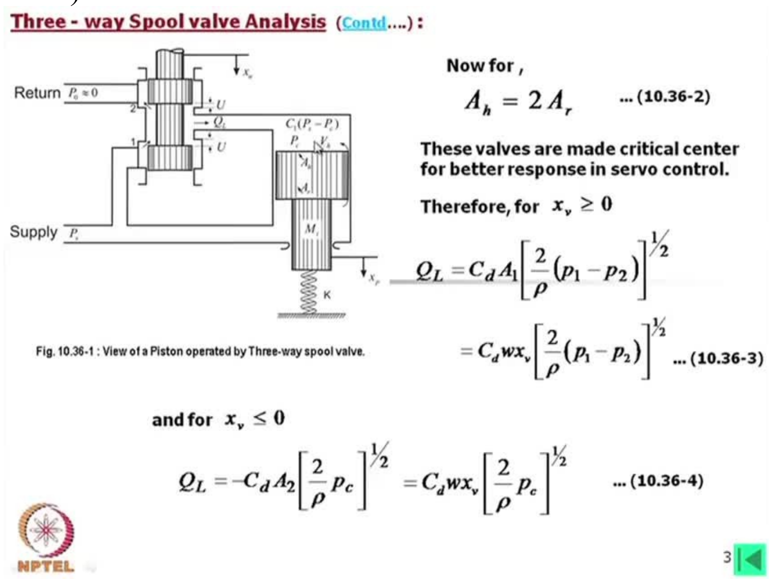

This is just you can express in the formula like this AH is equal to 2 AR. These valves are made critical center for better response in servo control. Do you understand my point? I told that maintaining the critical center is difficult. This means that to make such valve critical center, both these groups, dimension of the group, not only the width of the group, but also the distance between these 2 groups should match with the distance of the Spool.

And in fact I would say, matching these 2 dimensions in 2 different components is difficult and it is normally in practice if it is used for Spool, sorry the servo control valve, in that case the Spool and this is called sleeve. Actually you will find in our body, there is a separate sleeve is used for this outer member. In that case, these are made match parts. That means, say 10 set of spool and 10 set of outer members are taken together and then each and every Spool is matched with the member and then it is examined that really how much critical center it is.

It best pair is taken for one valve. Then perhaps next one. In that way, it may happen, in a 10 sets of these 2 components, these pairs, 5 components may be rejected also. This is one thing. 2nd thing, when it is under operations, then this adjustment because this is driven by some actuator, this might be electrical solenoid. Now adjustment with the solenoid positions and the Spool positions because the solenoid is not directly coupled.

It is, it will be directly coupled but not a single component. These are, the solenoid spool and this Spool is not directly, not an integral part. They are just connected. So sometimes this, it deviates from this critical center positions and that can be adjusted of course. Now it is found that critical because as I told this is for reversal operations. It means, it is some operations, it is doing forward and backward.

So if there is a if it is a overlap valve, then there will be difficult for position controlling or maybe this reversal time control. So in that way, critical center valve is better. Now for that critical center valve, if you recall for earlier analysis, general analysis for this Spool valve then this can be written as the load flow can be written in the form of coefficient of discharge into a1 is the area of this orifice and then 2 divided by this is the density of the oil and then P1 minus P2.

Here is the P2 and here is the P1. Remember, P2 is not equal to P0. P2 is the pressure here and this P1 is the pressure here. So we can further write this equation that CD into WXV. XV is the Spool stroke. It is called stroke. Stroke is XV. Now W is, what is W? W is the peripheral sorry periphery of the this you can say this Spool length okay. This diameter into 2 pi. Sorry pi into this diameter will give W.

Now this means that this is we are considering the rectangular port. Now W is written as if you remember in general terms. Sometimes, instead of this continuous, this this group is continuous. Instead of this continuous group, some rectangular holes are provided. If this is with rectangular holes, say 4, 5, 6 holes over the periphery and that are usually (inaudible 13:14), in that case also we can use this formula is equal to W because that W in that case, width of that each group each hole through a the sleeves plus the number of such groups.

Anyway, this into the stroke length will give the total area open there, that is the orifice area. And so this is the equation we can write for the load flow but when this is in the opposite direction, that is that means it is moving in the downward direction, in that case, this equation simply written as, we will consider the A2 and this is again you will find that it is in the opposite direction and in that case, only there will be the control pressure. That means, we are getting only control pressure over there okay.

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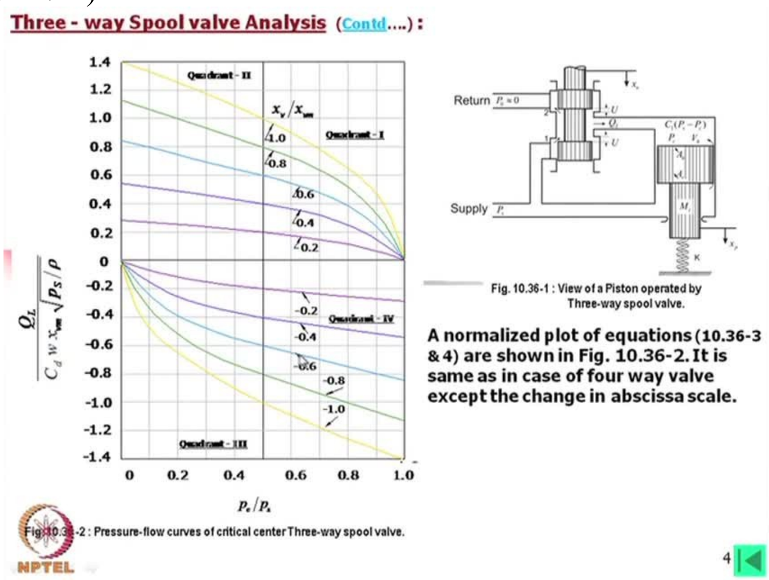

Now we can plot that what equations we have written there, we can plot. To study such say valve, performance of the valve, better to plot such graph and then we can understand that how it is performing. Now it is same as in case of 4 way valve, except the change in abscissa scale. If you remember, in what we have already studied the 4 way valve, in that case, you will find, in this axis, PC by PS is equal to 0 here and then it is varying in this directions, negative and varying in this direction, positive.

That is from the left-hand side to the right-hand side of this Spool. In that case, we simply use this value in this abscissa. Now here, this is written in the dimensionless form, this is also in the dimensionless form and we can observe these are the for different XB by X maximum okay. So this ratio. So all are in dimensionless form and what we find? We should call, this is the null positions okay? This is the null position.

Now at null, QL is equal to 0, XV is equal also 0. No, here it is the XV is 0 is here, not that. This is in the 4 way valve you will find this is the zero position whereas this is the position for flow and as well as for no we have considered XV is equal to 0, that means this is the 0. So this might be the curve okay at null positions. Now there what we find, the control pressure PC is PS by 2 because we have taken the area ratio, so at that condition PC by PS is equal to 2. That means, PC by PS is equal to 0.5, this means here. Okay, what we consider that UL is equal to 0 and our control pressure is here at null position.

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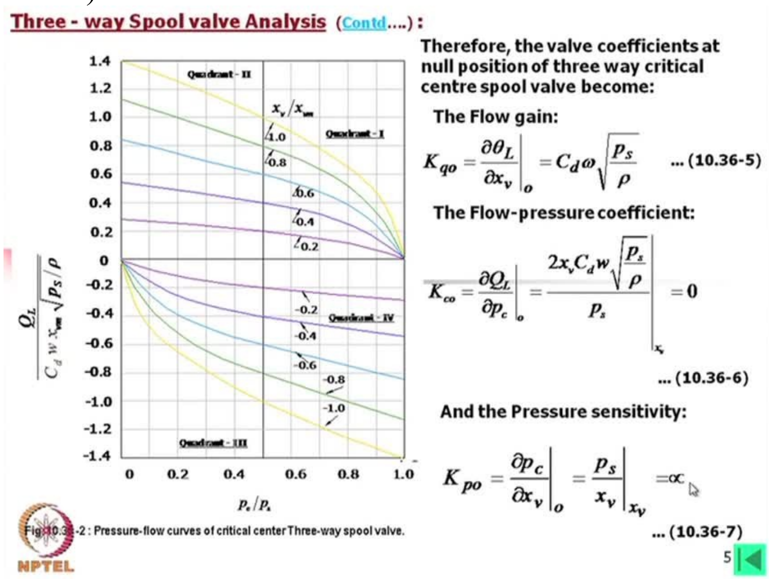

Therefore the valve coefficients at null positions of three-way critical center Spool valve can be written as from this if you have attended the earlier classes then you can find that Del QL by Del XV not theta L, this is Del QL. Okay? This is Del Q QL by T. So this is flow gain. That means how much gain will be there at null positions. This depends on that critical center or open center and this ultimately can be written in this form.

Next, we will look into the flow pressure coefficient, the low-pressure coefficient is written in this form. This is W, this also will be W, not Omega okay? Now the pressure sensitivity can be written in this form. Now what we find? That at null positions, due to looking into this curve, this will be 0 whereas the pressure sensitivity which is actually this divided by this, that will become infinity because this will have some value whereas this will become infinity. Which means pressure sensitivity at the null position is infinity means highly sensitive at the null position.

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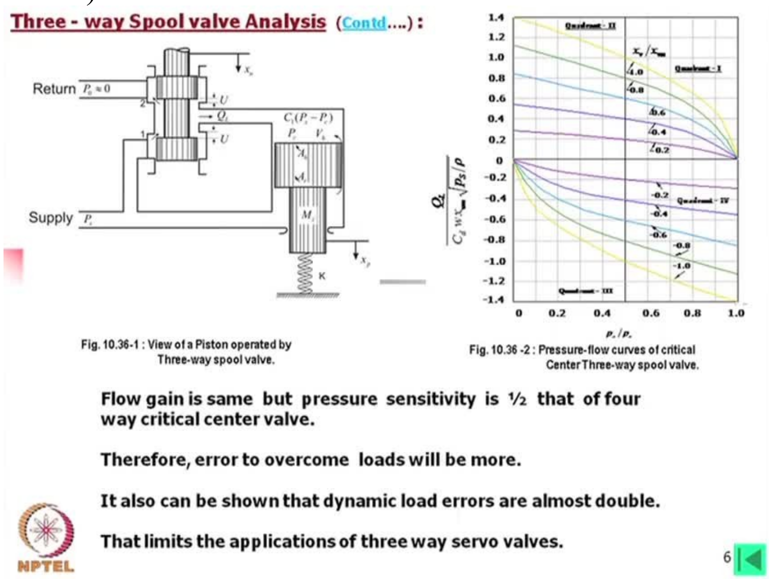

Now the flow gain is same. If you look into the 4 way valve flow gain, what we will find? In this three-way valve is also flow gain is same. But pressure sensitivity is half that of 4 way critical center valve. This is from the equations, you have to compare the equations of those I have not shown here and the equations of three-way valve. Therefore, the error to overcome loads will be more.

Now this we should understand that as the sensitivity is half of the 4 way critical valve, then the error will be more in case of three-way valve. This means that again, although the three-way valve is simpler in construction, and it is very good for using selecting such valve in case of the reversal operations, that is for the mostly for the linear actuators but what is there, the error will be more. That means, to rectify such error, we need much stronger, better controller than the 4 way valve.

It also can be shown that the dynamic load errors are almost double. This, due to this factor. That limits the application of three-way servo valves. So three-way servo valve you will find normally for the of course I would say the machine tools and at many places, these are used but if we look into the time response, that means we need very quick actions. Suppose we are trying to position control very accurately and with almost no time, real time control, in that case possibly, we will have to go for 4 way valve even if for if there are frequent reversal operations.

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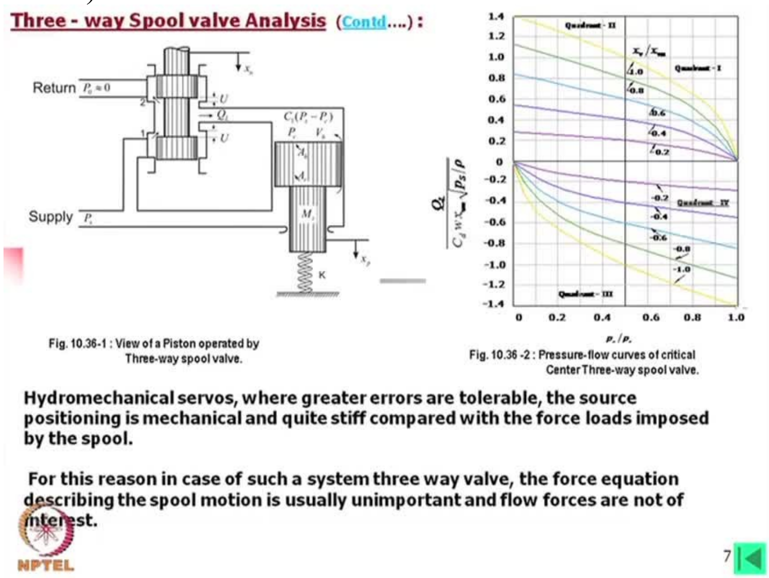

Now hydro mechanical servos where greater errors are tolerable, the source positioning is mechanical and quite stiff compared with the force loads imposed by the spool. For this reason, in case of such a system, three-way valve, the force equation describing the spool motion is usually important and flow forces are not of interest. Usually what we have seen that flow force has significant roles on the controlling of the spool in servo mechanism.

Now in that case, the argument is that the as these are we are tolerating the errors and the source positioning is mechanical quite stiff compared with the force load. So in that case, we can go for three-way valve where the flow force is not that significant.

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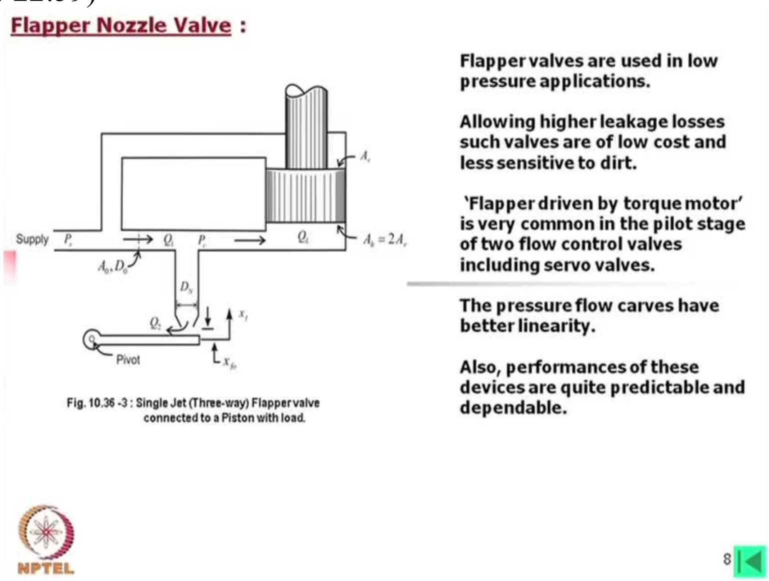

Now this is I have giving you the idea of three-way spool valve. Now similarly, there are three-way flapper nozzle valve also. In flapper nozzle valve, we will see some advantage over the spool valve. 1st of all it is less expensive but mostly, allowing higher leakage losses, such valves are of low-cost and less sensitive to dirt. This means that usually such orifice and you will find this flapper is moving, thereby this flapper area is being controlled, dirt can easily go out.

So therefore it is better than the fuel spool valve. However, always there will be leakage loss and that you should take of. And obviously the costing because making of a spool will be more expensive than such flapper valve. Flapper driven by torque motor, this is usually you will find that a torque motor will be used there. What is torque motor? We know this motor principle. In that case, armature is such that with this armature, it will generate some torque with the current.

If we increase the current, then the more torque will be there. If we decrease the current, so there will be less torque. This is very common in the pilot stage of 2 flow control valve including servo valve. Now if you look into the 4 way servo control valve, you will find in the 1st stage, there is two-stage actually because to drive the main spool, we need much force and sometimes what happens?

That there is a 1st stage valves which, through which the flow, hydraulic oil goes to control the main spool. In that case, you will find this first stage usually made of flapper nozzle. But here, I would like to mention, we will see that that flapper nozzle is normally it is by double flapper.

That means on the other side also, there will be such nozzle and flow is coming this way and from the other way.

But this is what I have shown here, this is a single one and we will, our basic analysis will be done only on the single one. Here also, we have taken this cylinder with the same 1 is to 2 ratio okay. The pressure flow curves have better linearity. Also performance of these devices are quite predictable and dependable.

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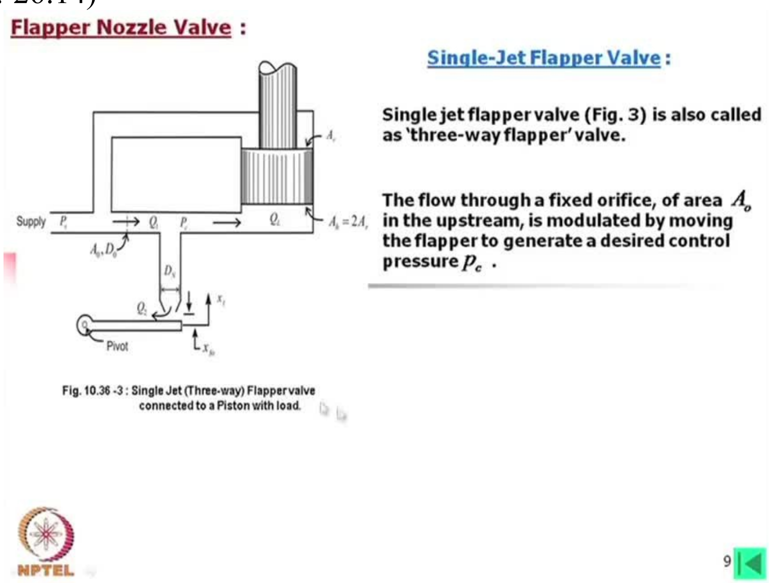

Now we shall consider the analysis of a single jet flapper valve. It is also called sometimes the three-way flapper valve okay because of this principle. The same we have seen, the same principle is used for the spool valve also. Now the flow through a fixed orifice of area A0 in the upstream is modulated by moving the flapper to generate a desired control pressure PC. Now here, we will find that a fixed orifice A0 is provided.

Now flow is going through this, now this flow can further be controlled by moving this flapper. If we move this one, this will be closed. You will find that pressure will increase and due to this increase in pressure here, here the system pressure is remains same, there will be less amount of flow and this will be controlled whereas in this directions, there is no orifice. So upstream means this we are calling the upstream flow.

The curtain area is more important than the flapper nozzle orifice area. Now this what is called curtain area? Now this we would call this is the nozzle area and this area which is closing this one, this is called curtain area okay? So this we have to know, one is called curtain area and another is called in the orifice area. Orifice area is this one and curtain area is what I would say that if I consider this periphery over here, into this depth, say this is initially XFO, this height into the periphery, that means pi into diameter here into this, that area is important than this orifice area.

The working range of the control pressure is estimated by obtaining the block load characteristics, expression of mathematical model are shown in the next slides and also you look into this block load characteristics.

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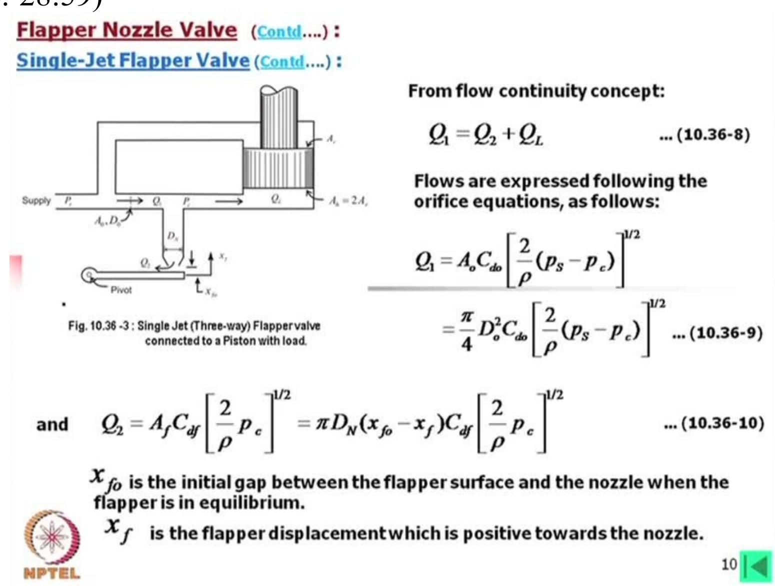

Now from the flow equations what we know? That Q1 will be Q2 plus load flow. That means, if we consider the this flow is Q1, then that must be equal to, one load is going this way and another load is coming, another flow sorry the flow is being divided into a part is for the moving the load, a part from the just exhaust. Now just controlling this one, we can control this low also. So speed control is also done by controlling this flapper.

Flows are expressed following the orifice equations as follows. Now the orifice equation is same, only thing in this case what we consider that A0 is the area, this is pi by 4 DO, DO is the diameter here okay? Now this is the system pressure and this is the control pressure over here. So this is the flow Q1, total flow. No, D0 is the diameter of this orifice sorry. A0 is the orifice here, so we are writing the equations for this orifice okay? Which is simply this is obviously we have considered a circular hole and normally it will be circular.

There is no reason making of other shapes, neither rectangular, nor elliptical or so. Simply a drill hole you can consider. Now Q2, this flow is equal to AF area of we should call this is the curtain area and that becomes pi DN XF0 minus XF, that is the curtain height and CDF. Okay? The DN diameter is actually this diameter. This is maybe drawn in a wide way.

DN is the diameter here, not this diameter , diameter of this orifice. So DN. So pi DN this periphery into the current curtain height will give us the orifice area here. So Q2 is expressed in this way. And here, the PC is the pressure in the upstream and in the downstream, is the exhaust pressure which is normally 0. That is why, this is here we find two pressure term, here the one single pressure down okay?

Now XF0 is the initial gap between the flapper surface and the nozzle when the flapper is in equilibrium. Now look at that, we should take care of the direction of XF. XF is the moment of the flapper which is positive in the upper directions okay? So this means when it is moving in the upper directions, this curtain height is being reduced because this is positive and here we have minus sign.

But suppose it is moving in the opposite direction, do not forget to put except itself is minus. So total curtain height will increase and total area will also increase. XF is the flapper displacement which is positive towards the nozzle.

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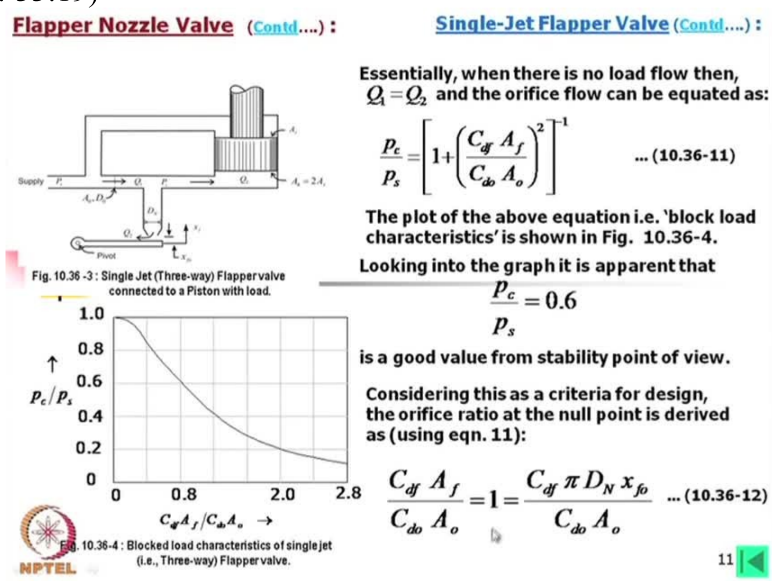

Essentially, when there is no load, there is no load flow, that means it is no load flow, then Q1 is equal to Q2. Or in other words, if there is if this is not moving, that means we want that it should not move but still and this is open, then whole the oil coming in, that should go out. In that condition, Q1 is equal to Q2 and PC by PS if we write in that way, this will become, this will be expressed in this form.

The plot of above equation that is the block load characteristics it is called block load characteristics, this can be presented in this form ok. So if this is the this ratio is varying from 0 to 2.8. Now how it can be 0? The AF itself is 0, this area is equal to 0. How? This means that this is completely closed. That means, XF in positive direction is equal to XF0. In that conditions, what we will find, that PC is equal to PS. Okay? This is one.

Now if we this extreme case what we have considered, 2.8 that in that case of course, this is the ratio, remember, see here to make this is 0, we consider AF itself 0 but this ratio when this is this has some value, then this ratio depends on the coefficient of discharge area, et cetera, however what we find? This is of course for a particular valve.

What we find that 2.8 of this ratio, that PC by PS is 0.1 only. That means control pressure is 10 times less than the system pressure, okay? So this diagram is useful for to find out the operating conditions. Now looking into the graph, it is apparent that PC by PS is equal to 0.6, is a good value for stability point of view. Now why we say this value is from stability point of view, this is because of the reasons that if we move in this directions, then definitely, we will find that control pressure is much much lower than the system pressure and in that conditions, we do not have much control over this load.

So what we find? That possibly if we be here then this is of course this is simply a just a common, maybe this was found by the analysis that at that conditions, the operation will be the best. Whereas if we if we enter in this zone, say this is 0.6, if this is a 0.8 perhaps, this is 0.6 or this is 0.4, this one must be 0.6. PC is equal to 0.6 is this one. Here it is 0.8. This is considered as a stable condition stability point of view.

If it is in this side, what we will find? That controllability will be difficult because it needs more accuracy whereas in that case, controllability will be difficult due to the fact that the control pressure is too low. Considering this as a criteria for design, the orifice ratio and the null point is derived as now this value, we would like to put 1 because this pressure we want half, PC by PS is half. So that means, this we would like to put 1. So this ultimately derived into in this form.

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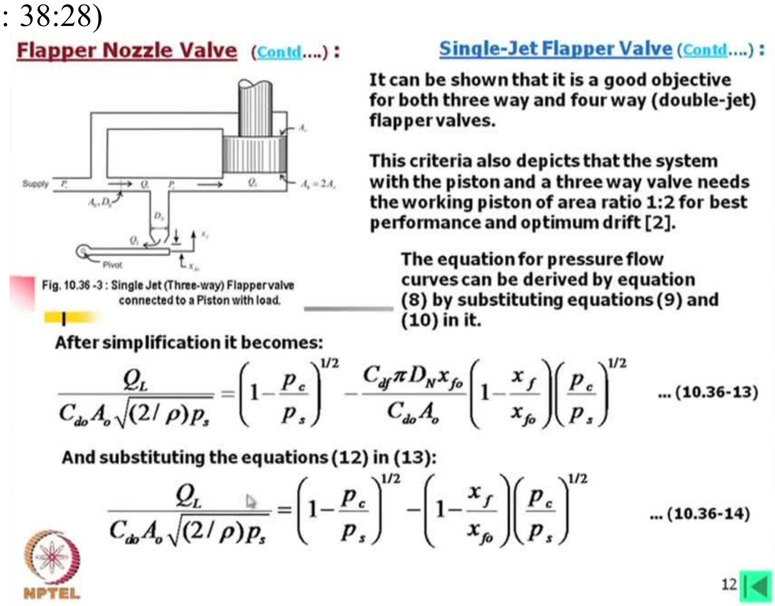

And then it can be shown that it is good for it is a good objective for both, 3-way and 4 way. For way mixed double-digit. Remember, when there is another nozzle in the opposite directions which we call the double-jet, this will be the 4 way flapper valve. This criteria also depicts that the system with the distant and three-way valve, needs the working piston of area ratio 1 is to 2 for best performance and optimum drift.

Now this, about this drift, we should go to the to know more about this drift, we can consult the reference too which I will show later but what is drift? Drift means that while we are using such 3 valve, 3-way valves then we are moving the load, both in plus minus directions. So this means that it is operating something. And in most of the cases, you may find, this is operating a another spool.

Now what is drift? You will find that when this is at the central positions, this spool, this piston cylinder what we have called but this is basically controlling a spool, that should be in such a position that that spool is also in the null positions but due to the leakage and error, what it happens? When this is in the mid-positions, this may be what it is controlling, that is in not in the null positions.

So this null position and that null positions may not match. So that is called drift. Now there is also technique that we can control the drift also okay? But this is important. However we are not analysing the drift, this do not know about this drift, we should consult these references. The equation for pressure flow curves can be derived by equation 8 and substituting equation 9 and into 10.

And then, this , this equations become like this. So this is for the pressure flow curve we derive this equations. You just substitute this and you can arrived into this equations. Now similarly, substituting 12 and 13, we get this equations okay?

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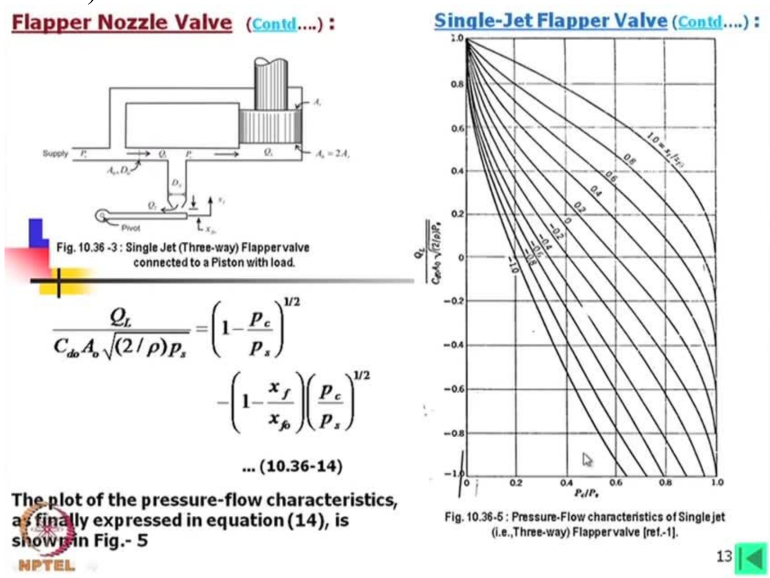

Now we can perhaps if we look into this equation, then this is plotted here in this curve. And this plot of pressure flow characteristics is finally expressed in 14 and this is presented here. Now if we look into this, in this case also this is same as the spool valve. So abscissa is same as it is different from the 4 way valve but here only we have considered only one side of this curve. In that case, obviously, this flow is this is 0 because the load flow can take in both the directions and what we find? That XF by XF0 is here. So this is basically the null positions sorry this is coming over here. This is null positions whereas for the moment of XF in both the directions, we get different curve okay? So from there we can find out the valve coefficients.

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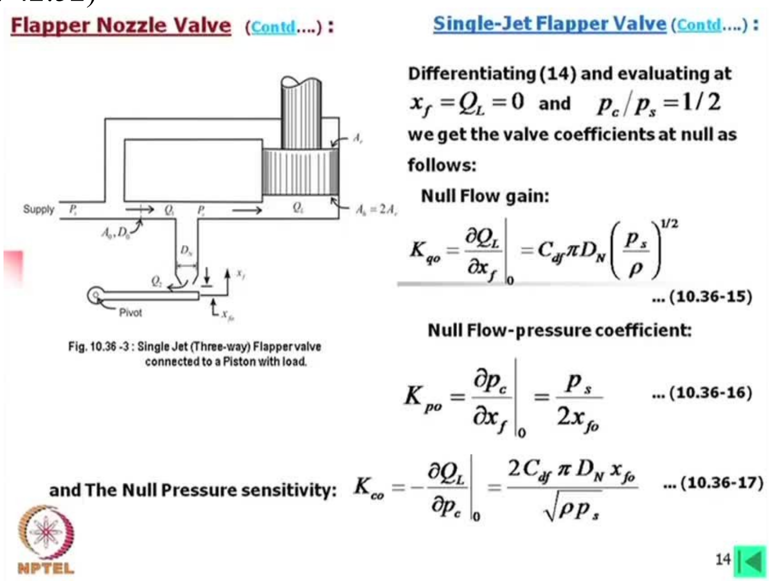

Now if we differentiate 14 and evaluate at XF is equal to QL is equal to 0, that is for the null positions and PC by PS is equal to 2, sorry PC by PS is equal to 1 by 2, then we get the valve coefficient at null positions. And these are we can find we can express in this form. And null low-pressure coefficients is expressed by this as well the pressure sensitivity is expressed by these equations. Now this is important to know the null for each and every valve, for 3-way, 4 way. So null coefficients are important to understand how better is the valve in performance.

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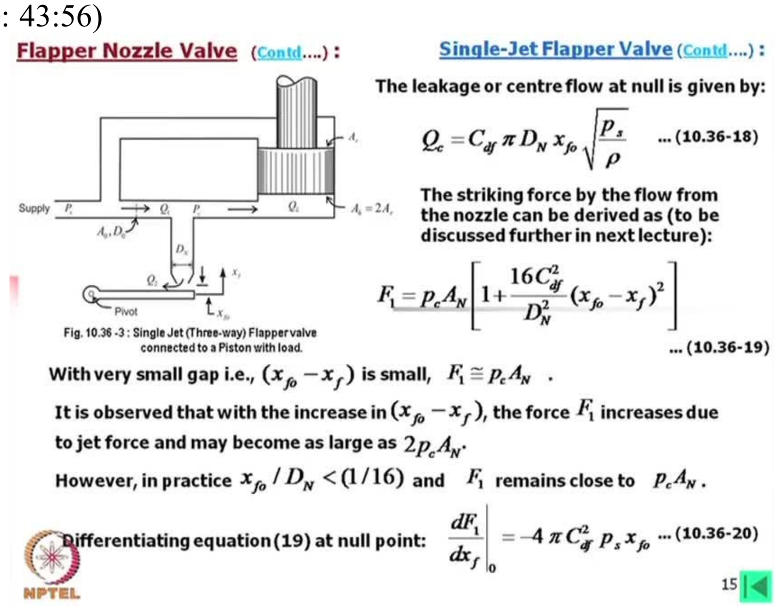

The leakage or central flow at null is given by these equations. Now here in it is important, although it is a center sorry this is a critical center valve but still there will be some flow, some leakage flow. If you, we have earlier discussed about the central flow. The central flow is important for a valve because that affects the flow gain okay? But this leakage can be expressed in this form.

Obviously, in case of flapper nozzle, there will be leakage because we should not say the critical center flapper nozzle valve because these 2 nozzles by no means we will sit on this flapper because there will be some. This means that there will be leakage. So knowing this central flow is important for this flapper valve. Now the striking force by the flow from the nozzle can be derived as in this form. We shall also discuss in the next lecture.

Now what is striking force? The striking force means this when the flow is coming on, then this is striking on this flapper which is ultimately required to estimate how much torque is required. Okay? So this F1 is limited by this formula. With a very small gap, if we make this gap is very small, that is in the null positions or maybe in the even in the operations while we are moving this XF in this direction is, this gap is being reduced. Then for very small gap, what we will find? F1 is equal to PC into AN.

What is AN? AN is the simply this area, not the curtain area okay? It is observed that with the increase in XF0 XF minus XF, is that that gap, the force F1 increases due to the jet force and may become as large as twice PC into N. Now look into this. Normally if the gap is small, this force is PC into AN whereas if this gap is increased, this force becomes double. Or in other words, I would say, this we are equating here but in other words, I would say this flapper valve are designed in such a way, you will find that with small gap F1 is equal to this and with the maximum displacement of with the maximum gap the maximum increase in this, this force become double.

Or in other words, within this range, we design the torque motor ok. So torque motor is selected in such a way that there will be twice the torque from the minimum torque required to operate this valve. However, in practice, that XF0 by DN, DN is the diameter here, is usually 1 by 16. So suppose if DN is equal to say what I would say? 1.6 millimetre diameter of the this nozzle is 1.6 millimetre in that case XF0 is only 0.1 millimetre. 0.1 millimetre you can imagine is very small.

So and again we are giving the portion of that. So this motion is very small and very precision. And F1 remains close to PC into AN. Differentiating equation 19 at null point, we get this expression, DF1 by DX0 is this much.

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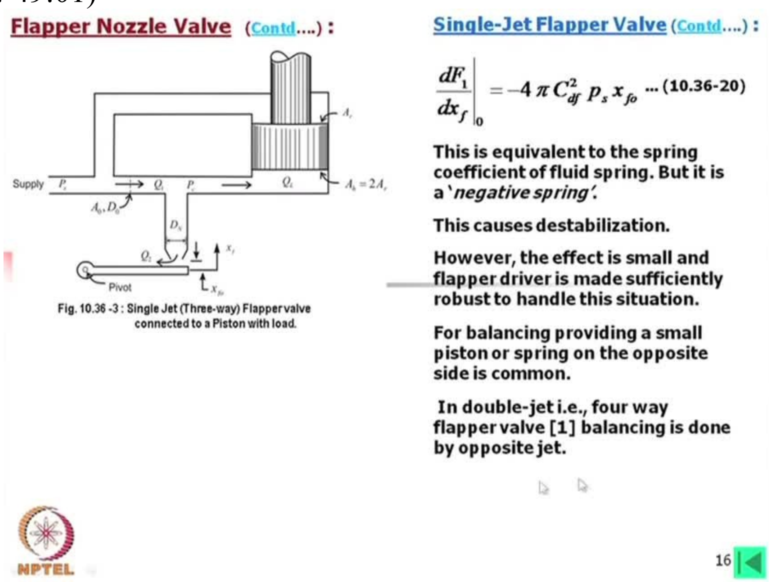

Then this is equivalent to the spring coefficient of a fluid spring. Okay, if you compare this, we can, if we consider the mechanical spring, this is as if a fluid spring with this much of stiffness. But it is a negative spring. What does it mean? What is negative spring? So normally, with the increase in when this is the gradually when it is being compressed, mechanical spring, the load is increasing. Here it is opposite.

This cause a destabilization okay. Due to this negative nature, a destabilisation is observed. However the effect is small and flapper drive is made sufficiently robust to handle this situation. This means that while we are designing this torque motor, we have to consider this part and it should be robust so that it can handle such de-stabilisation. For balancing, providing a small piston or spring on the opposite side is common.

Sometimes a spring is used in the opposite side. That is for the flapper nozzle. What happens if for the if there is double nozzle? In that case you will usually find a springs are used here in both directions okay. In case of single nozzle, you can use this spring directly opposite otherwise you can use also a coil spring for both directions. In double jet 4 way flapper valve, balancing is done by opposite jet. This means that in case of opposite jet, if there is another nozzle in the opposite direction, sometimes we do not need any spring at all because this can be balanced by the opposite 1. Okay?

Now we shall continue our lecture in the we shall discuss more about this flapper nozzle valve in the next lecture.

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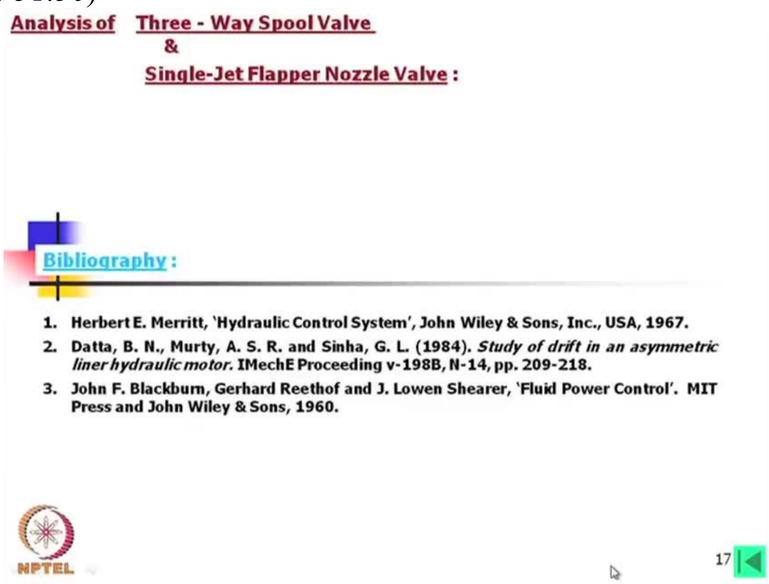

For this lecture, the mostly I have taken from the this meritts book which is hydraulic control systems, also particularly to know about the drift, this paper is important. So you can go through this paper and there are some general idea from the Blackburn, book of Blackburn and Reethof and Shearer. Thank you for listening.