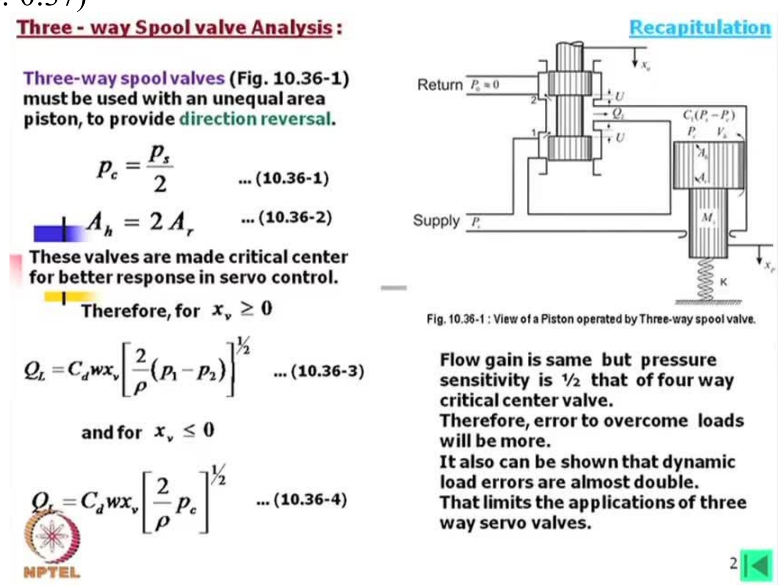
Fundamentals of Industrial Oil Hydraulics and Pneumatics
By Professor R. Maiti
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur
Lecture 38
Analysis of Flapper Nozzle Valves

Welcome to today's lecture, analysis of flapper nozzle valves. This is a continuation of our previous lecture which was on 3 way spool valve, as well as an introduction to flapper nozzle valve.

(Refer Slide Time: 0:37)



Now if we recapitulate, then 3 way spool valves used with unequal area pistons to provide direction reversal. Now in most of the cases, we have found that for way valves are very common, used in fluid power. If we control say rotary actuator say in motor, in that case, we prefer 4 way valve because there the direction reversal is not very frequent. In comparison to that, where the linear pistons are used, then due to the frequent reversal, it is found that 3-way valve which is cheaper than 4 way valve, can be used.

Also, this has advantage with Jack the linear actuator of unequal areas. Unequal areas means in it is head side usually, there is no rod or even, it might be on the either side of piston, there are piston rod but that piston rods are of unequal area. Now also, we learned that this **is this** will be most advantageous if the control pressure is half of the system pressure. Now why it is like that?

We are trying to control something, then apparently they are having pressure on the both the side of the actuator and then we try to control.

The main reason is that, this can be explained like this. Say for example, we would like to say suppose this is an indicator. That indicator we would like to put a particular position. Now if I try to control with one hand, definitely we can do it but it is always better if we try to control this by 2 hands, that means creating pressure from both the side and we are moving this. So for the position control and the as well as the force control, jacket is always better that this pressure from both the side.

And that is why, Jack in you will find in servo control there is pressure on the both the side. Obviously, there will be loss, definitely there will be flow and pressure loss but from the control point of view, this is unavoidable. Now in three-way spool valve, what we find? That the oil, this is the supply oil and this supply oil has direct entry to the rod end side of the piston and there is entry to the other side or the piston head side through this control flow okay?

This means that while we are opening this side, if we keep it closed, then supply pressure is going this side and this is being moved up in upward direction whereas if this is open, then oil is going through this and this orifice is controlled in such a way, part of the oil will go to the control Jack side or in other words head side of the piston to control the motion of this piston and a part of the flow will go back to tank.

Now for this pressure ratio which is perhaps the best for the control of such a three-way valves and this pistons, unequal pistons, the area is also half, I mean area ratio is half. Or in other words, the area of this piston divided by the area of the ringside is equal to 2. Now these valves are made again critical center for better response in servo valves. Now you see this, what is critical center valve? Critical center valve means the this is just critically left, that means width of this, ideally width of this groove and width of this, length of this spool is equal.

Ideally, dimensionally if we consider the nominal dimensions, they are equal. However, to maintain the tolerances, because even if this is closed, there will be radial clearance through which there will be leakage. Usually you will find, if we measure the dimensions very accurately, dimensions of this length is slightly more than the groove width okay? Anyway this critical center valve will have very less bandwidth.

That means, at the null positions, there will be less loss as well as the response will be very quick. This means that if you move in either directions, the response will begin almost immediately. So as we need frequent movement, I mean reversal motion of this piston, so critical center spool valve is the best. Now if we recall our earlier development of the formulations then we can Jack write down the load flow for the displacement is in the positive directions, that means in this directions Jack yes in this direction, then this equation is written as the CD, the coefficient of friction and this is the Jack total area of the orifice.

How? The W is the width and XP is the spool displacement Jack. Now W is width in this case is the total peripheral length of the spool or so to say inside of this groove. That means in this case directly we can get W is equal to pi into D, that is diameter of the spool or DP, whatever it might be. And then, this flow here, this load flow we are considering this P1 and P2 is the pressure difference. So that will be the flow. Pressure here is P1, here it is P2.

Now for the other directions then the flow is load flow is given by the PC is the pressure, control pressure there. Then other pressure is the 0. So PC into to buy rho root under root and this is the again area of the orifice, CD should be determined experimentally but normally for such a spool where these are just are very sharp, normally this CD can be taken the (())(9:24) model which is around 0.6 2.63 something like that. So normally we do not need to go for any special experiment for such valves and Jack but the W in case of Jack the that full open valves, that means the full groove, the W is equal to pi into D as I have told but sometimes what is it is there, **(in style)** instead of this groove, continuous groove, we may have rectangular hole.

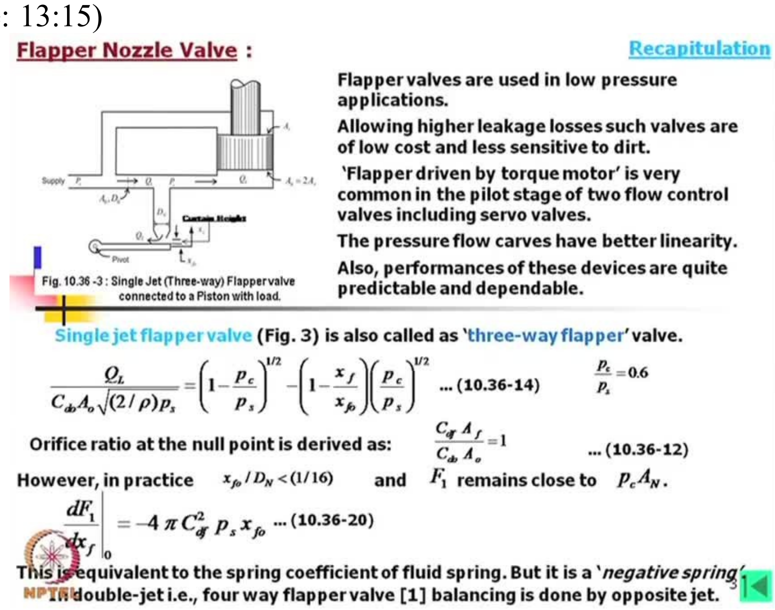
Then the length of this hole along the spool sleeve is equal to the the side of the spool length for critical center. However, this groove width we sum up to get W. say for example, there are 4 groups which perhaps only spread over 15 degree or 30 degree, then we simply add this W to get Jack the orifice, opening area. And if this if there is a some circular grid hole or some other type of hole, then these are calculated accordingly.

However, in most of the cases, we will find that this is the linear port opening Jack. That means rectangular port, we will get this rectangular port which is here, the hole is rectangular or the full groove. Now flow gain is same but pressure sensitivity is half. That way, 4 way critical center valve. This is if we recall the 4 way valve analysis and compare the flow gain, that is the different coefficients, valve coefficients, then flow gain coefficients shows that here, this is pressure sensitivity is half whereas flow gain will be same as that of the 4 way valve.

Due to this reason, error to overcome loads will be more. In case of three-way valves, this will be more. Then why the why the three-way valve? 1st of all, it is very less expensive and it is better or quick control can be achieved by this arrangement, three-way valve arrangement. However, this is for the control we have to look into this error. It also can be shown that dynamic load errors are almost double then in comparison to 4 way Center valve. That limits the application of three-way servo valves.

This means that we need to control the error. There is no way that we will allow the error. That means, that will be deep thread but the question is that to eliminate such error, how much time we can spend? If there is we need to control it within very short time, very response, in that case better to choose 4 way valve. Otherwise where we can have, we can allow more time for such control, for such eliminating errors, in that case, we can go for three-way valve.

(Refer Slide Time: 13:15)



Now what is Jack flapper nozzle valve? We find that in flapper nozzle valve that instead of in case of the three-way spool valve, we have seen that spool is controlling the flow. In that case, that means basically it is allowing the oil to go to the ringside, ring end side of the piston end while we are trying to control that motion of this system, we are allowing the oil on the other hand side but that flow we are controlling by three-way spool valve. In that case what we find?

Say if we compare with that previous one, then oil is allowed to go into rod in rod Jack this sorry this piston head side but that is again controlled through an orifice and a part of the oil is allowed to go back to the tank through an orifice the opening of which is controlled by cantilever beam. That is basically a plate, a very thin plate is mounted, pivoted on a Jack pin, this pivot and then this is moved by some mechanical. In that case, we call the torque motor is there.

So this means that like the other one, like the spool valve 1, the supply oil can freely go to the rod and side. If it would like to come in the head side, in that case. 1st of all it is going through a fixed orifice, the hair orifice is fixed. In case of spool valve, this orifice is also varying. This is also varying. But in this case, this is a fixed orifice and fixed orifice and this is being controlled. Another thing is there in in such control that instead of this opening which is circular obviously, this orifice area, the important area is that curtain area.

Curtain means if we consider the diameter which is DN, pi DM is the periphery, periphery into that height is the curtain area and that area is important in this case, not the directly this orifice area. Then flapper valves are usually used in low-pressure applications where the pressure is relatively low. Now it allows higher leakage losses and such valves are of low-cost and less sensitive to dirt. What it is? In case of the most crucial problem in hydraulic is the dirt particles.

In case of servo valve where these components are almost matched part, this means that sleeve diameter and the spool diameter is made such that we get minimum leakage loss and very high sensitivity in any flow. In that case, if dirt comes in between, then problem becomes, either this will damage the spool or the whole operation will be stopped due to these dirt particles. And thus controlling this dirt or we if the dirt comes in, breaking that dirt into smaller particles or removing, allowing this dirt to go in this other side, all such mechanism is done to design a very good valve.

On the other hand, there is also research is that if we allow this dirt to go with the flow and easily it can go through this leakage part, then it is seen that in instead of spool valve if we use this flapper nozzle valve where this opening is relatively more, the particle can go out directly. And it does not stop the machine at least, stop the function at least. Although there will be some disturbance. So in that way, flapper nozzle valve is better than spool valve.

So this is the biggest advantage using the flapper nozzle valve. Now flapper driven by torque motor, as I told that there will be an torque motor. Torque motor means it is not rotating fully and its output, of course output of motor is torque. In that case, this torque motor means it is just giving a small amount of torque, actuation is small, in one direction, it can rotate in the opposite direction, say if the current sense is reverse and these are used to move such flapper.

Now again in that case, what we look into this? This is comparable with three-way spool valve and we have that single flapper jet application of the three-way spool valve mechanism. This is acting as a three-way spool valve but in most of the cases, the application of this flapper valve is at this pilot stage of 4 way valve. What it is? I will show later that if we use this that in also in the other directions, then we can imagine here a spool, 4 way spool valve.

Now that 4 way spool valve again is being used to actuate another spool valve which is also 4 way which is actually the main stage of the valve because in many cases, the load is so high that if you we a single state school, then it **di** becomes difficult to control that spool okay? The spool force is very high and with high force, control becomes difficult. Then, to move that spool, 4 way say 4 way spool, we had another stage where spool is very small Jack.

We need to actuate that spool valve with very less amount of force which is controlled by this flapper knowledge Jack nozzle and these nozzles are at both the sides and then that main stage controls, that pilot stage control the main stage. That you have seen the earlier, in the servo valve section. So this is there are the basic application of such flapper nozzle valves. However, this is also used for three-way valve, used as a three-way valve for actuator control of unequal area.

Now the pressure flow curves have better linearity. Although there are losses, more laws, but we get better linearity. So control becomes easier. Also, performance of these devices are quite predictable and dependable. That means, where we do not need very quick response, we can allow such losses. Then for the low-cost applications, this is better than spool valve, 4 way spool valve.

Now single jet flapper valve which we have learned in earlier lecture is also called as three-way flapper valve. We should basically call it flapper valve but once a single the valve is there, then we call it 3 way flapper valve. Now for that load flow equation where which we have derived earlier, what we find? That load flow divided by this orifice area, that is the fixed orifice A0 into that this is the coefficient of discharge there, this area is nothing but pi D0 square by 4 okay?

And C0 D0 is the coefficient of discharge here. Then we get PC by PS, that is the control pressure by the system pressure, this will be definitely less than 1. So this term is always a real term and then XF divided by XF0 where XF is the Jack flapper motion and XF0 is the initial gap there, initial gap okay. Now this PC by PS is usually found 0.6 is good for such flapper nozzle valve. In Jack in case of spool valve, 0.5 and in this case, 0.6 is better.

Orifice ratio at the null point is derived as this CDF is here, the coefficient of discharge into AF is the this curtain area and divided by the fixed orifice area into the coefficient of discharge Jack there. And if this ratio is maintained 1 at null position, then the performance of such a flapper nozzle, single jet flapper nozzle valve will be the best. Now again in practice, that fixed gap divided by Jack diameter of this orifice is usually 1 by 16. That means, you can imagine **this** this diameter if this is say 1.6 millimeter, in that case, this will be how much? This will be 0.1 millimeter okay?

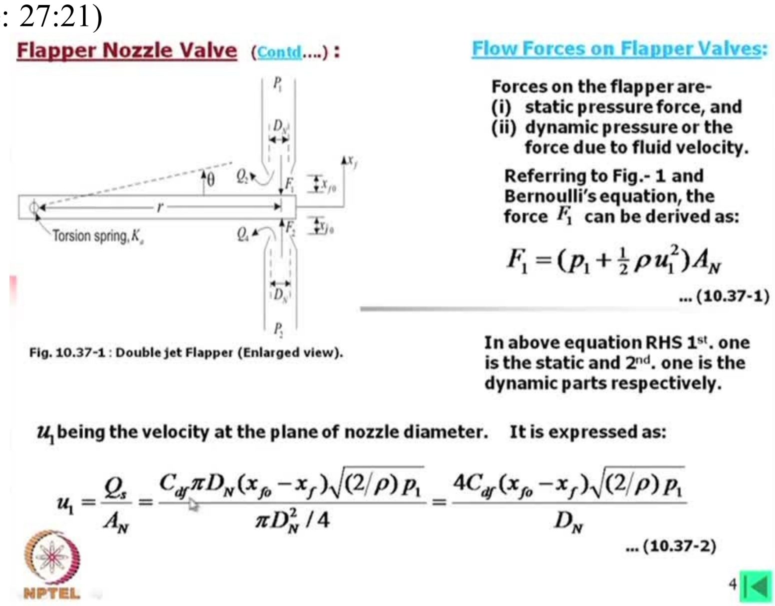
This gap will be 0.1 millimeter. And usually this flapper nozzle valve, you will find that of that range. We will see this later. And F1, F1 is the force due to this flow here, remains also PC and AN. AN is the area of this whole, not this curtain area. Just compare with this, AN is this area, okay? Now what we find also that if we differentiate this force with the flapper nozzle movement, then this becomes 4 pi into CDF square PS into XF0.

And this is equivalent to the spring coefficient of fluid spring okay. If we compare this value, then we find as if this is a fluid spring. But it is in the negative, it is a negative spring. What does it mean? In case of positive spring, this force increases with the when this is compressed, say this is Jack or the tensile press is being tensioned. But it is other way. In that case, if we reduce the length, then the force Jack will increase.

And due to that, control becomes a problem. So how it is controlled? In case of single flapper jet, we usually use a spring here in the opposite direction. But if we use the double jet, in that case, opposite side also there is a nozzle. So we can control the flow from both the sides and this balancing problem will not be there. It will become very easy to control the motion of this flapper. Therefore, double jet is very common where we use the flapper jet valve.

And as it is mentioned here, this is usually used to control the pilot stage of a main stage servo valve or so.

(Refer Slide Time: 27:21)



Now if we look into these waters the forces on the flapper, this **this** is, one there will be static pressure force. Now here, if we look into this flapper nozzle valve with double jet, then you can see, the tao Jack this it is working. **(sa)** Suppose if we would like to move this flapper in this directions, we need to have more force than that, this means that F2 should be greater than F1. You see, if you would like to move, you can make this is 0 but if we would like to move this one with a controlled motions, then this should have a force and this should have also a force okay.

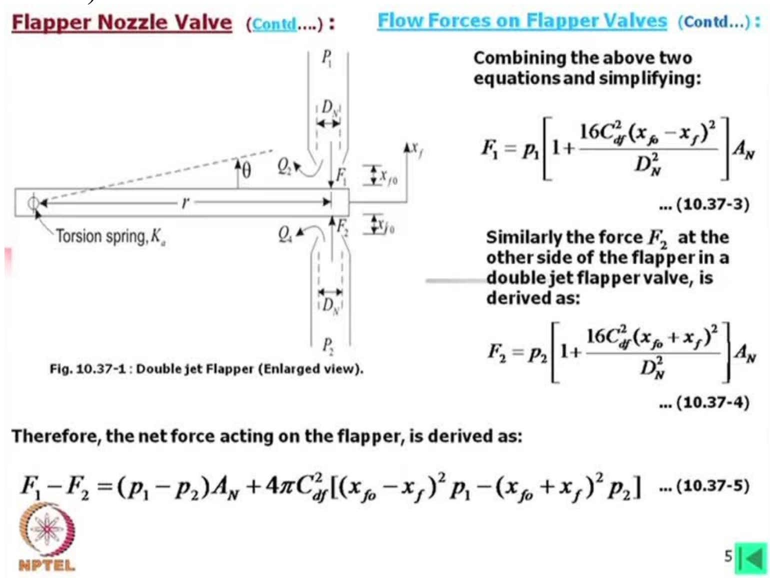
Now this is done in valve operation. There is also dynamic pressure of the force due to the fluid velocity. What is static pressure? Simply static pressure is will be equal to P1 into this area, not the curtain area. Curtain area, that orifice area is used for the load flow and other things but normally when we are calculate the force, then we consider this area which is equal for both the nozzle. However, the pressure will be different whereas dynamic pressure is that if Jack while we are considering the dynamic pressure, in that case we have to consider the velocity of the fluid which is impinging on this flapper.

Now referring to this figure, then I am considering the Bernoulli's equations, F1, that is the force can be derived as F1 is equal to P1, we are calculating this force, F1. Then P1 then rho U1 square into AN. AN is area of this orifice, whole diameter okay. Now what is here? In the above equation, right-hand side, right-hand one, 1st one is the static and 2nd one is the dynamic part. So this is the static part. That means, P1AN static force and half AN rho U1 square is the dynamic force.

U1 being the velocity at the plane of nozzle diameter. That means this velocity, oil how this oil is going? It is going like that. It is coming like this and going in this directions. Now we should measure the velocity along this perpendicular directions and at the vicinity of the surface of the flapper, that velocity is called U1. Now it is expressed as big equation, that is QS by AN and then CDF. The QS is the flow through this nozzle which may be Q2 and Q4 here. Pi DN then no here this this is the while we are calculating this flow, as I told that we will consider this curtain area.

So this is the curtain area into 2 by rho into P1 under root. That other pressure is 0. So we consider the P1 whereas AN is the area of this whole. So this is pi DN square, that is the diameter of this nozzle opening divided by 4. And if we equate further, this will arrived into this expression.

(Refer Slide Time: 31:43)



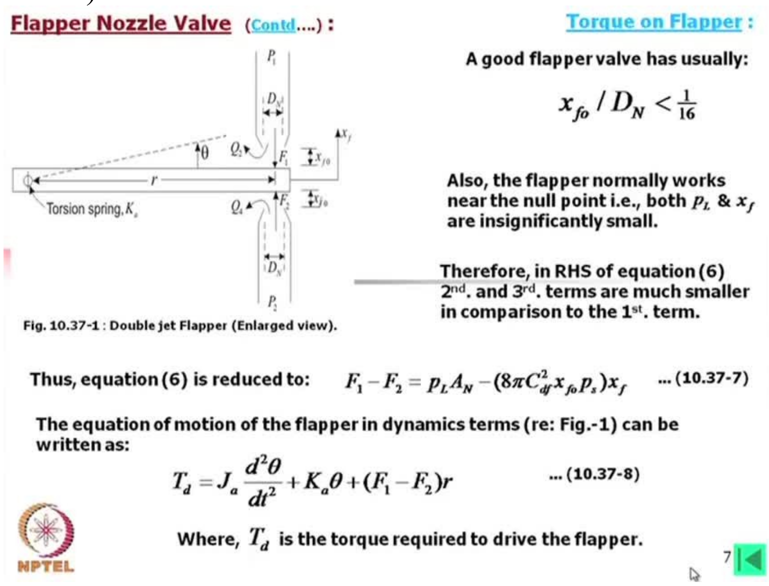
Now combining these above two equations and simple sign, what we get? F1 is equal to P1 into 1 plus 16 CDF square XF0 minus XF whole square divided by DN square into AN. Similarly, if we equate the F2 in the same way, we will get this F2 will be expressed in this form. Okay? So this is not difficult. But look into this, here we get minus sign, here plus sign. Why it is minus signs? In that case, we have considered that this is the positive motion.

That means XF is positive in this directions. So while this flapper is moving in this directions with say theta positive also, then this length is being decreased. So physically, this initial distance minus the spool moment will give the will be used to find out the curtain area. In this case, due to this motion, this height is being increased. So this will be plus sign here. Now if XF itself is negative, then automatically, this will be corrected.

So this equations we can use, this is the general form of the equation okay? Now Jack then this controlling force. As I told that force from both the directions, so this must be F1 minus F2, this might be negative also because F2 might be more than F1. But anyway, this can be expressed in this form. Simply we have subtracted this from this one. And this is the final form of the force.

Now combining the again two equations and oh sorry this is the perhaps the same this is perhaps by mistake it has been copied. So we will go to the next slide.

(Refer Slide Time: 34:05)

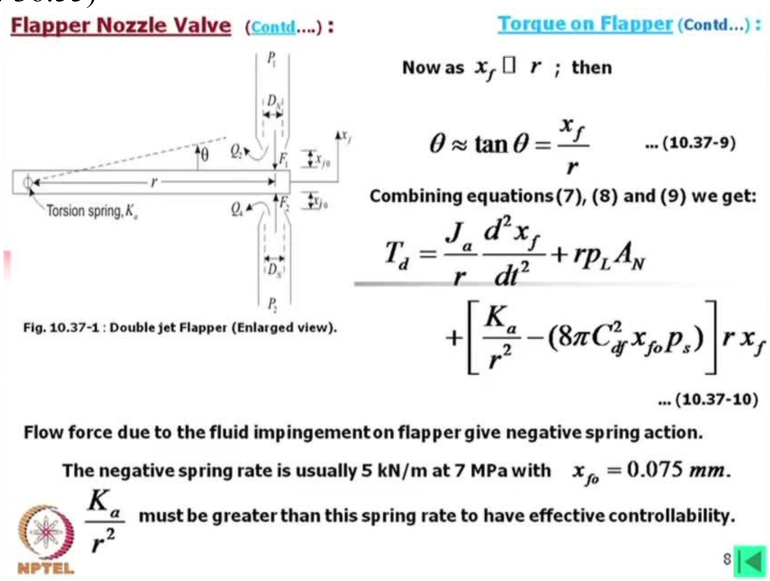


Now a good flapper valve has usually XF0 by DN is 1 by 16 that which we have learnt in earlier lecture. So this gives, this is a very good value for designing such valve and also, the flapper normally works near the null point, both PL and XF are insignificantly small. That means, normally this is for as we are trying to control the pilot stage, in that case load flow, load pressure is small as well as this motion is also very small because in case of, because this is basically the high-pressure process, the main valve. In that case what we have found, this valve opening is very small.

This XF, this motion of the valve is very small but that will generate a large flow due to the pressure difference. Anyway, this if these are too small therefore the right-hand side of the equation 6, earlier 6, 2nd and 3rd terms are much smaller in comparison to the 1st term. And then finally, we you have to see if you look into that equations and then we can neglect to terms and we can have, this is the usable equations to estimate the controlling force okay. Then we calculate the torque on flapper.

That means, how much torque we need to operate this one. The equation of motion of flapper is in dynamic terms can be written as this TD is equal to this is the inertia and then D square theta by DT square, this is the torsional spring stiffness into theta and this is the force into R is this. Now here, Jack I would say that this flapper may also deflect okay? While we are calculating this torque, we do not care about that. But while we are really calculating with the motion of theta and we are trying to relate XF0 we have to careful about that. Where TD is the torque required to drive the flapper.

(Refer Slide Time: 36:55)

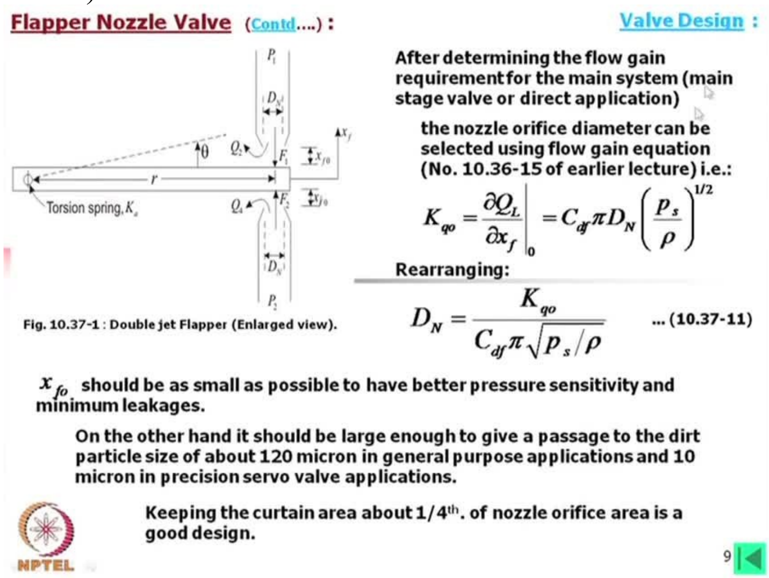


Now as XF is much much less than RF, there is some problem with this compatibility. This is actually XF is much much less than R, that means this length and XF is the spool moment and for that money can consider tan theta. Actually we have to consider the tan theta which is XF by R is equal to almost equal to Theta. And therefore this we can combine this 7, 8 , 9, these 3 equations and we will get the torque equation in this form.

Even have a look into these equations and this Jack equation is used for estimating the torque. Flow force due to the fluid impingement on flapper gives negative spring action which already we have learnt. The negative spring rate is usually 5 kilonewton per metre and at 7 megapascal with XF0 is not not 7 not 0.075 millimeter. You see this how small it is. Even less than 0.1 millimeter okay? And then actually this is this value is just a realistic value, this is to understand this what are the parameters, parametric values of such flapper nozzle valve okay.

And KA by R Square, K is the torsional spring stiffness, must be greater than the spring rate to have effective controllability. That you can understand if **if** this is not greater, then **we can** we will not be able to control it. So we according to this value, once we decide this value, 1st of all we estimate this one and from there, we have to estimate this one and accordingly we can design or select a torque motor for a flapper nozzle valve.

(Refer Slide Time: 39:22)



Now after determining the flow gain requirement for the main system, main stage valves or direct applications, main stage valve means Jack that means this flapper valve we are using as a pilot stage or we are using this Jack say directly for controlling the actuator. What we do? The nozzle orifice diameter can be selected using the flow gain equations. We use directly this flow gain equations and from there we **(fa)** find out what will be the diameter of the nozzle.

Say what, how much flow gain we need, from there we can have this value as well as have this value. And CDF we can have from the experience we have to take because we have not yet designed this nozzle. However, we know this what oil is being used, what will be the system pressure and from there, we estimate the diameter of the nozzle. And rearranging this equation gives in this form. Now XF0 should be as small as possible to have better pressure sensitivity and minimum leakage.

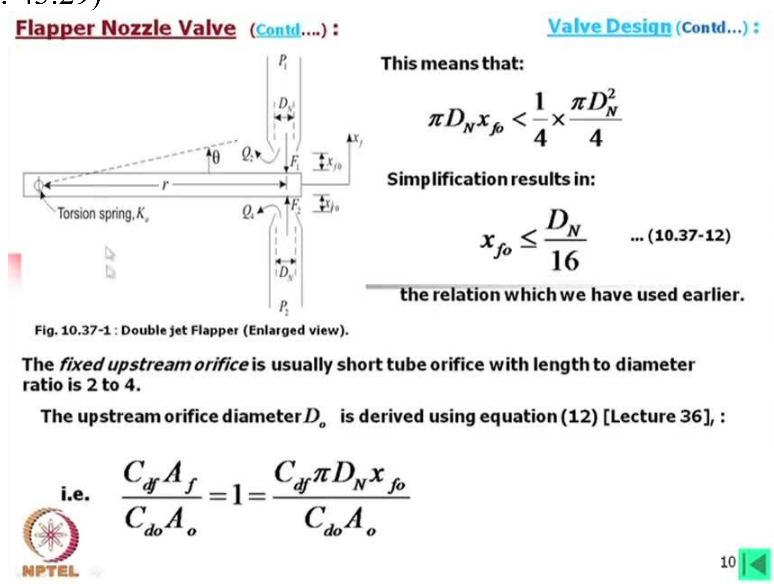
On the other hand, it should be large enough to give a passage to the dirt because basically flapper valve is used to allow the dirt particle size of about 120 micron in general-purpose applications and 10 micron in precision servo valve applications. You see normally in ordinary valve, general-purpose valve, we can allow the particle of 120 micron.

In that case usually you will find, after the pump, we can allow this flow directly to the valve and before the pump, we have only a strainer which is in the range of at the most, 150 micron or something like that. 120 micron, this value if we use this value, then probably, that is 120 micron. You can understand, this is 120 micron particle size means the filter we have used it is a (())(42:06), the diagonal length probably is of that size, 120 micron or so.

But in case of servo valve where the servo applications we are doing, this gap is very small. It **it** can if the particle size more than 10 micron, then it becomes difficult to move that valve. In that case, usually a high-pressure filter is used after the pump and before this valve okay? So we need a high-pressure valve, again using a high-pressure valve definitely a loss to the system but this we cannot compensate because such a control is definitely expensive but we need to control. Say for example, machine tools, even missile control, et cetera.

Keeping the curtain area about one fourth of nozzle orifice area is a good design. So this is just we are considering the valve design. So this value, it is from the experience if we maintain such relations, then the valve design will be better.

(Refer Slide Time: 43:29)



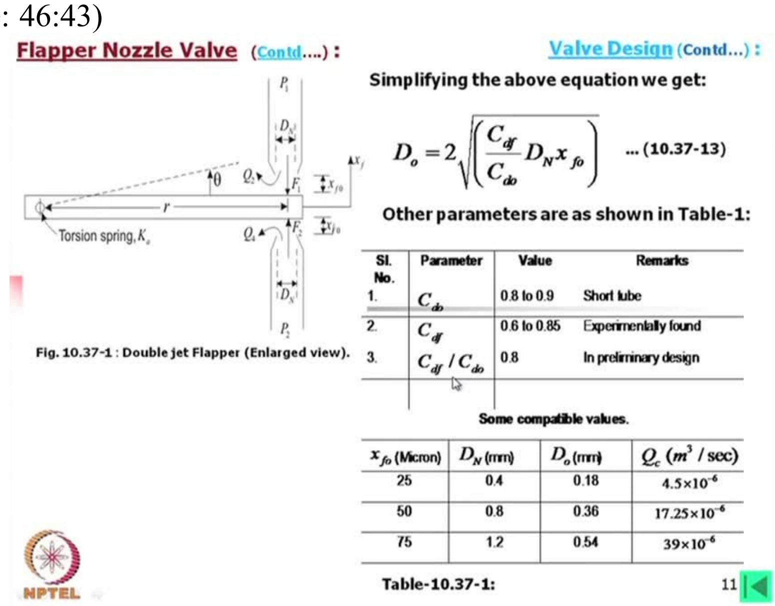
Now this means that pi DN XF0 is less than one 4th into pi DN square by 4. Specific results this simplification results in XF0 is less than equal to DN by 16 which we have already which we are using. The yes this relation already we have used. Anyway, the fixed upstream orifice is usually short tube orifice with length to diameter ratio is 2 to 4. Again, another important factor is that say this is the orifice opening and this is the length of this nozzle, what should be the length we can Jack no, this is not this orifice, we are talking about this other orifice here.

That has to be there to control the flow. Both the side, this orifice will be fixed orifice will be along with this tube. Now in that case, usually there a short tube orifice with length to diameter 2 is to 4 is used. That means, orifice are of different type orifice are used in sub valve valve control. In that case, we can imagine that that orifice is that within the tube there is a plate. In that plate usually there is a hole, simply drill hole and the ratio of the length to diameter is 2 to 4. If diameter is 4 unit, then length is only 2 unit.

Say 2 millimeter thickness means at the most 4 millimeter diameter is the hole. But usually we find, very thin plate and very small hole is used and usually a straight hole. In some cases also, hole with an inclined entry or maybe (())(46:02) it is used. Normally straight hole is the best. Now from this diameter and the length ratio, we can find out the coefficient there. There are different models but we will see some realistic data.

The upstream orifice diameter D0 is derived using this equations. We would like to maintain this ratio is equal to 1 and from there, this is AF is the that is the curtain area and A0 is this upstream origin sorry orifice area okay? Now this again can be written in this form.

(Refer Slide Time: 46:43)



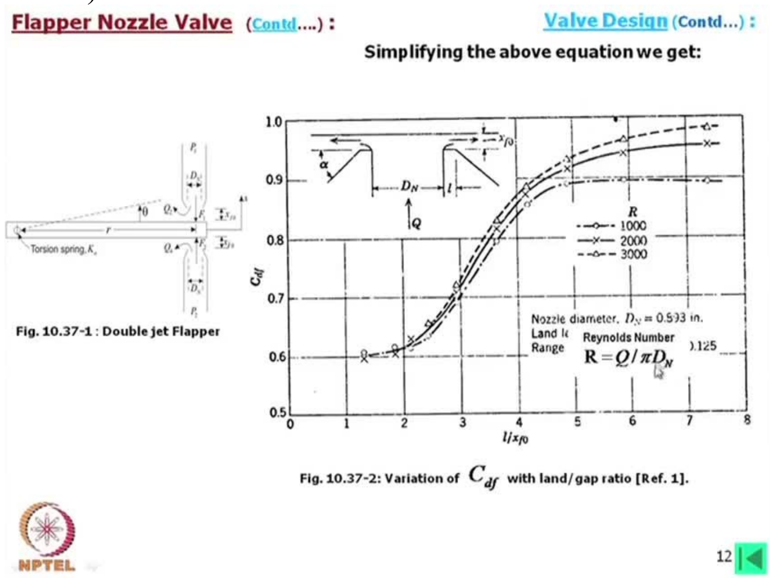
And then simplifying the above equations we get, D0 is equal to that as the fixed orifice diameter is equal to 2 root over CDA by CD0 into DNXF0 okay? DN is the diameter of this nozzle. Now other parameters what we find is you can see that CD0 that is the coefficient of discharge at the this orifice, you see this is in the range of 0.8 0.9 whereas normally be find that 0.6 is the good value from for the orifice. That means this is actually capillary short tube.

Here it is written itself. Because in comparison to encase of these orifices, the length is very small, very thin plate and then there is a hole. Whereas in in these cases, certain length is there but it is found that using some such short type short tube orifice is better for the from the control point of view. And Jack as we find, whereas this is 0.6 to 0.85, that is if we consider the coefficient of discharge here, this is 0.6 to 0.85. And usually CDF by CD0 is preliminarily designed.

That means when there is no movement of the XB is equal to XF is equal to 0, in that case this ratio is a good design. Now if we consider the realistic value, say XF0 is 25 micron, you can imagine how small it is, then DN is 0.4 millimeter only whereas D0 0.18 millimeter and the flow there is 0.45 into 10 to the power minus 6 meter cube. That means, it is no, it is some 4.5 this value we call, this meter cube means in **in** relation to the cc, 10 to the power 6, yes, so 4.5 cc okay? So in Jack if it is 50 micron, then this is 0.8 and this is 0.36 and 17.25 cc and if it is 75 micron then 1.2, 0.54 and this is 39.

This is to have an idea that what **(uses)** usually the flow. Say you can consider this is perhaps for the direct valve and this is maybe for the pilot stage. And this might be for the pilot stage of very big valve.

(Refer Slide Time: 49:57)

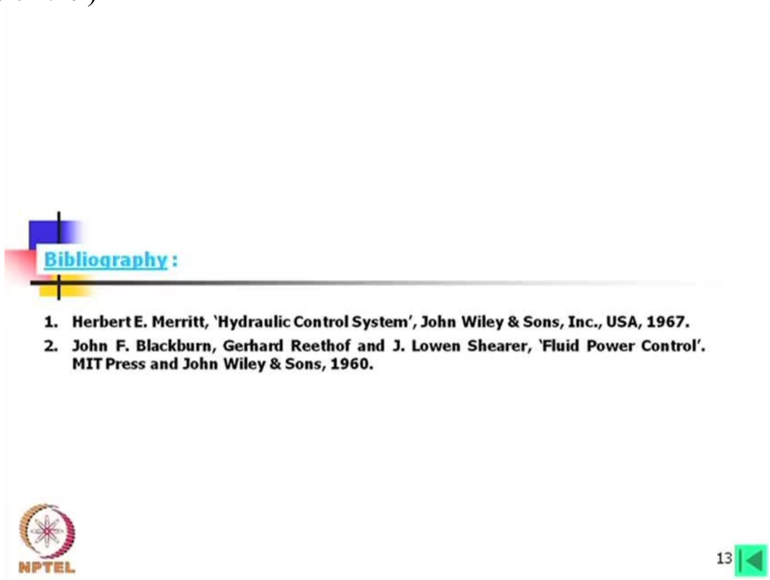


Now again so this is sorry this is not properly much. If we consider that some realistic data, more realistic data on this, what we find? This is DN is of course it is given in inch, 0.893 inch. 0.893 means here it is a quite large one okay? And then there will be Reynold's number Jack Jack say 1000, 2000 and 3000 and for that, what we get? The coefficient of discharge is varying from 0.6 to almost 1.9598 something like that.

And it is more at large Reynolds's number and that means the high velocity flow and it is less with the less Reynolds's number. Now and this is the ratio of L into XF0. What is L? L is the we can see that this is the nozzle actually okay? And this is the curtain height and this nozzle means if we say suppose if we decrease this L, that means it is almost a tapered hole, in that case that this say L is less means this is we are in this side, so coefficient discharge will be less whereas if you go on increasing this coefficient of discharge will be more.

And Jack this alpha angle, this value is not given here. I have no idea also what is **the this** Jack this alpha angle is there. So this is some realistic value to understand how this nozzle is designed.

(Refer Slide Time: 52:29)



And this is mainly we have followed this merritts book, this is hydraulic control system and also some idea is taken from the Blackburn, Reethof and Shearer's fluid power control book. Thank you for listening.