Fundamentals of Industrial Oil Hydraulics and Pneumatics
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Lecture 39
Flow Force Compensation and Spool Design

Welcome to today's lecture entitled flow force compensation and spool design. This is continuation of the lectures on Electro-hydraulic valves. I have put this into a special topics miscellaneous topics because this is some detailed idea about how to design a spool and how to compensate the flow force.

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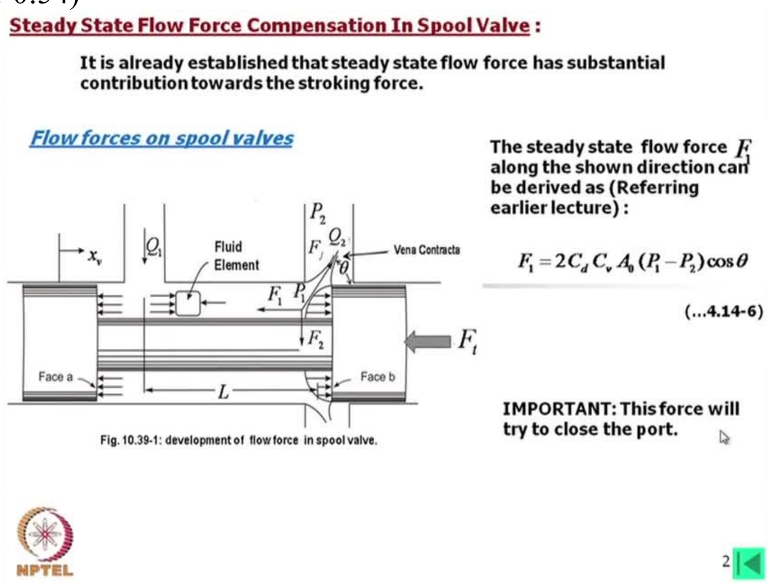

Now it is already established that steady-state flow force has substantial contributions towards the stroking force. If you look into this figure which you have seen in earlier lecture that how the flow force is working on the spool. If you look into the spool, say let us consider the flow is coming like this and it is going out like this. This is full rectangular port, this means that there is a groove here and so if we consider the length of this orifice will be pi into this diameter and width is the opening which is XD.

Now for this configuration, we know, this flow will neither touch this valve nor touch this length with a some sufficient velocity or in other words at very low speed and some valve configuration, it may touch this length or this valve. Otherwise it will make an angle to this path which is theta and it is possible to predict this angle theoretically. Now what is happening? If we consider this spool, on that spool, there is a force on this valve.

This is the pressure force. Similarly the same pressure force is in the opposite direction in opposite phase of another land. Then we should consider then these 2 will be balanced. But if we consider this Z, then definitely, there is a force because this oil is moving in this directions. If we follow the Newton's laws then there will be force and that force if we resolve, this will have one in the lateral direction and another in the axial directions of the spool. Now this force is called flow force.

This flow force I mean at the steady-state condition if we look into this flow force, direction of the force acting on the spool is in this direction. That means it is trying to close this path. And? Now while we are estimating what is the force required to move the spool, then this flow force having a contribution, substantial contribution towards this total force apart from the other this force when the spool is accelerating, we have to consider the mass of that and if there is pressure imbalance anywhere, we have to consider that force also.

So total force is calculated in that way but this force maybe 30 percent, 50 percent of the total force. So if we can reduce this force, definitely then control of the spool because we have to drive the spool with some force, some actuator. That actuator if it is a hydraulic actuator, then there is less problem. But if it is solenoid drive, that means electrical drive, in that case to generate that force and control of that is difficult.

So better to reduce this force if we cannot eliminate it. Now this force this F1 the which is the steady-state flow force can be estimated like this which we have shown earlier. Now CD is the coefficient of discharge, CV is the velocity coefficient, A0 is the orifice area, P1 and P2 is the pressure difference and cos theta is the Z angle. That derivation is shown earlier. Now this is important, I have already discussed. This force will try to close the port.

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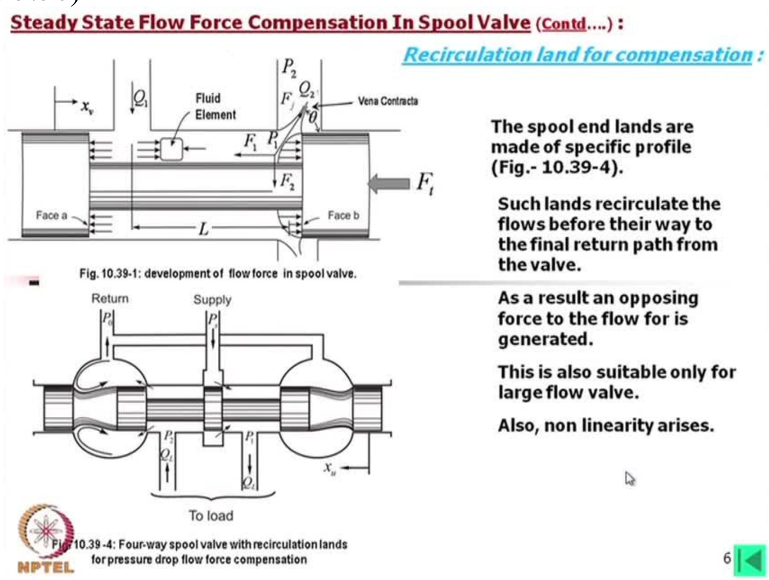

Now let us consider a large valve. Again it is 4 way, 4 way valve of spool diameter 25 millimeter. Once we say that spool diameter, this means this large diameter. Other is called stem. So spool diameter means this is 25 millimeter. Stroke of 0.5 millimeter, that is the XV is 0.5 millimeters at pressure 7 mega Pascal. Then the force the stroking force may be estimated as large as 80 Newton. This considering the acceleration of the spool also.

If this this spool has constant velocity, then there is no force. But when this is accelerating or decelerating, there will be additional force. So summing up all such force, it is 80 Newton. So with hydro mechanical devices for stroking, handling such a force is not a problem. However, for electromechanical devices, it is nearly the upper limit of available generated force. Now upper limit, this term although we have used, we can go for bigger solenoid but looking into the size of the spool, normally the size of the drive solenoid should not be very big than the valve.

So in that case whatever the solenoid size we can provide with this dimensions, we can see that this is almost the 80 Newton is almost the upper limit of the available generated force. In designing direct drive valves because these valves may be this this is the main spool, maybe direct drive which are gaining popular for more reliability in some areas like in aircraft applicable, it becomes crucial. This means that sometimes I sometimes? In many operations, instead of pilot operated, valve, the direct drive valve is preferred, the response is better.

Now pilot operated valve as I have mentioned, that is called two stage. So that is like it is like that when there will be some signal to move that, the spool will move the pilot stage. Now through this pilot stage, this may look identical like the spool valve but small spool. Then there will be a small force which will be diverted to this either this end or in the opposite end which will generate this force maybe say 80 Newton or that level to move that spool.

So that can be done. But response of such valve is much less. So in many cases, direct drive valve is required. Then for direct drive valve, we cannot use this or even if we use that hydraulic, against some controllability problem will be there. So in that case, if we would like to use the solenoid, better to reduce this force. So this is the only area which we can reduce. That I have mentioned.

Therefore reaction of flow force is desired, both for direct drive single stage and also if in case of pilot operated it is better if we can reduce this force. Now proposed methods of steady-state flow force compensation by modifying the spool design are generally employed okay? So one is that we can work this design of such spool as well as maybe the sleeve because this is not the direct body of the valve, usually this will be a sleeve.

So we can modify design to reduce such force. It increases the manufacturing cost definitely if we want to this is very simple. Just a step down instead of that if we would like to modify this profile, naturally the manufacturing cost will be more and even increase nonlinearity in controlling the force. Sometimes due to this curve or maybe some profile which I will show, nonlinearity will increase. But still, reaction of this force is required.

Now one can think of many matters but all may not be acceptable due to the nonlinearity in control or to too much increase in the cost of manufacturing but there are some popular design which are accepted for flow force compensation. Now one is that Z angle modification. Say for example, if we can make this angle 90 degree, that means straight directly to is going in the upward directions say, then definitely there will be no component in this directions.

And one can see this you may ask that but F2 will be there, F2 will be large. But F2 is uniformly distributed over the circumference. If not uniformly distributed, it might be discreet but at a certain angle, equal amount of force. So that will cancel each other. So we can make this theta 90 degree to make this flow force 0. But it is not possible by providing this groove design.

One way of making the Z angle 90 degree not even not exactly 90 degree but close to that is that instead of making the rectangular groove for port in the valve sleeve, say this is rectangular port, very common. For that rectangular port because this machining may not be that difficult, so flow can go like this. So this is the 90 degree. Sorry this this is this is the Z angle. So for for rectangular port, we cannot reduce this theta to 90 degree reduced or maybe we would say that make it 90 degree it is not possible.

Then what we can do? We can provide the rectangular hole at different positions, maybe 4 at 90 degree, maybe 6 at 60 degree or more but making such rectangular hole on the sleeve is difficult. Say one is that electrohydraulic sorry that is nonconventional machine, electro discharge machining or something can be provided but for mass scale, obviously it can be done with the use of broaching. How it is done?

That 1st we make an whole, circular hole by drilling. Say if it is a 90 degree, just 2 Cross hole we can provide there and then using a broaching tool, we can make this square hole. So but it is seen that if we make such square hole, then this flow Z angle maybe 90 degree very close to that. Okay? And then if we can make it is 90 degree because Cos theta will be 0 in that case and there will be no component in this axial directions okay.

It is to be noted that the rectangular holes are better, not the circular holes in compensation of linearity also serve the purpose. This means that as I told, we make a circular hole, then we broached it. Instead of that, we can have a circular hole there also. That will serve the purpose, that means that will compensate the force however this will there will be more nonlinearity due to that.

Now larger spool end diameter is also another solutions. What it is? We can make this land diameter more also the stem diameter as you see here is more than what is at the middle. Now in that case what happens that due to we have to make this groove depth and here also depth in such a way we can see this angle is more than this normal angle. It is close to 90 degree and the flow force is reduced, not fully compensated but it is reduced.

This is to increase the flow rate and thus the pressure drop in the opposite side of the flow force to have more force opposing the flow force. This means that usually large diameter means there is a orifice opening because this length is more. So for a stem stroke, orifice size will be more, there will be more flow and the pressure drop will be more. In that case, the pressure is compensated okay. It reduces the flow force to some extent.

However, this is effective only for large flow valves. That means if we use such say for example as I told that 25 millimeter diameter, that may be around 25 litre per minute flow rate, very high flow rate. For that valve, okay, it is okay, 25 millimeter is a large dimension if we think of this valve design, spool design. Therefore it is possible to compensate to some extent this force.

Moreover, such compensation named as pressure drop compensation, it is we call it large spool and diameter from the end diameters this is from the spool configuration but actual the mechanism is that pressure drop compensation is not effective for partial orifice port valves. So that means if we use that rectangular ports a few rectangular ports instead of full port, it will not work. Another method is that there is circulation land for compensation.

Now in that case, let us look in this valve what is happening. This spool end lands are made of specific profile. This profile is made like this okay? Now also the sleeve group is made like this. But still if you look into this, the port is the orifice is rectangular, for rectangular because orifice area is calculated this stroke length into pi into this diameter. So this is rectangular but instead of rectangular groove, this is somewhat spherical groove inside.

Now for that we that whatever flow is coming, due to this profile, it is recirculating. This once it starts recirculating then this although here is the Z angle but due to this flow, there is another force, so that force counteract to each other and in that case the total flow forces reduces but if we look into this, what this is a obviously special design, not as simple as this. For that what will we have? What we will have?

Such a lands recirculate the flows before their way to final return path from the valve that I have discussed. As a result and opposing force to the flow is generated. Now but this design again usually made for very large flow because for the small spool giving such profile is difficult. Also, nonlinearity arises and apart from the cost giving a special profile.

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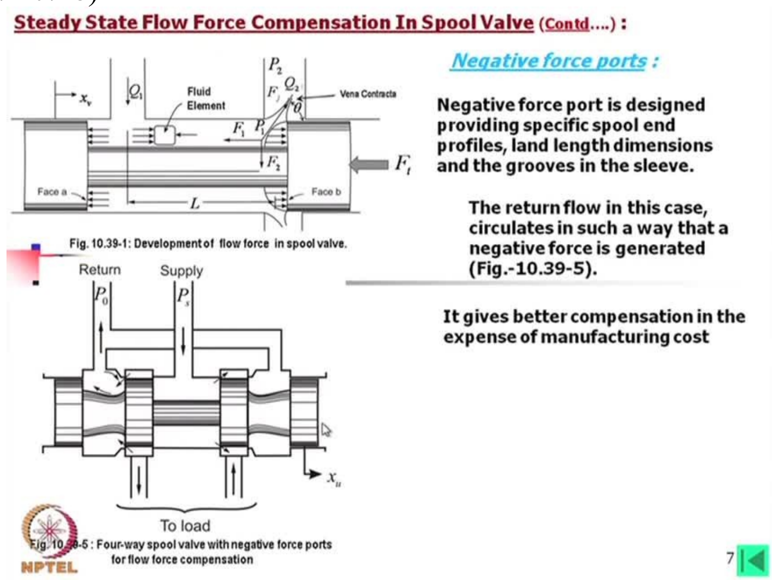

Now another possibility is that we can generate some negative force by designing the port accordingly. Now for that, what we find? Negative force port is designed providing specific spool end profiles and land length dimensions and the grooves in the sleeve. If we look into this in comparison to the earlier one that it was a spherical, instead of that it is stiff and an inclined surface.

Due to that as you look into this, instead of flow moving in this directions, here it is of course moving in this directions, on the other hand it is moving in the from here to here it is moving in this directions. And there is a recirculating. Due to that the force is negative. It becomes, it can be calculated, design can be made such that flow force is negative. That means, this will try on the valve and ultimately to move a spool in this direction, total force will be less. Now it gives better compensation in the expense of manufacturing cost.

If we can use this type of port, then it is better but manufacturing cost is high.

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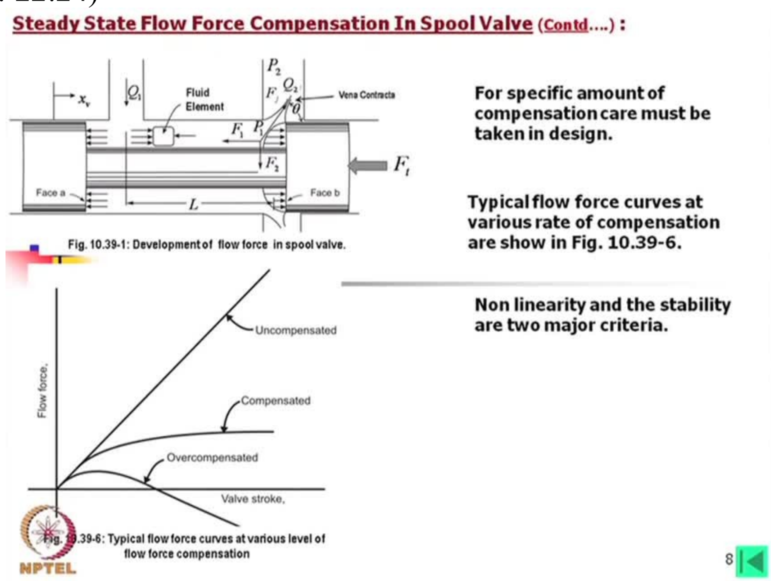

Now these are the few methods which I have shown. For specific amount of compensation, care must be taken in design. Say if we this means that if we can optimise something, it is not always expected that the flow force will be 0. We can have some flow force and designing the drive, that means designing the solenoid or any other drive and keeping the compensation force to a limit, we can have some optimum design.

Now using such methods, what type of compensation may be available? This is described here. Say for example that this is uncompensated. That means, if we take this type of valve directly, then what we find? That this flow force will increase with this valve stroke length okay? This is almost linear for this type of port. Now if it is compensated, a good compensator valve is something like this.

Now this say for example negative port sometimes it may become overcompensated. Now overcompensated is having a difficulties because this due to this flow force in that case, the it is trying to open. What we are giving? We are giving the force in the direction of the stroke. But if flow force overcompensated means flow force is trying to open the valve. That means, if we keep the valve without any force, due to the flow force if there is leakage, that will try to move.

So controlling of overcompensated valve is difficult. Nonlinearity and the stability are 2 major criteria. Now nonlinearity we understand. Say for example, this is type of when it will come, that will what we will find? The force not always a constant. It is varying, again not linearly varying.

Then controlling of such force will be difficult, I mean it is nonlinear control we have to introduce. And stability is another point.

Stability means that when we are moving this spool, it has dynamics. Then we have to stop the spool at a particular position because we want a definite movement of the spool but what happens at that conditions? Starting at the starting point particularly at the stopping point, it will try to vibrate. So we have to consider about that part also. It might be sometimes that flow force is better from the control point of view of the stability okay?

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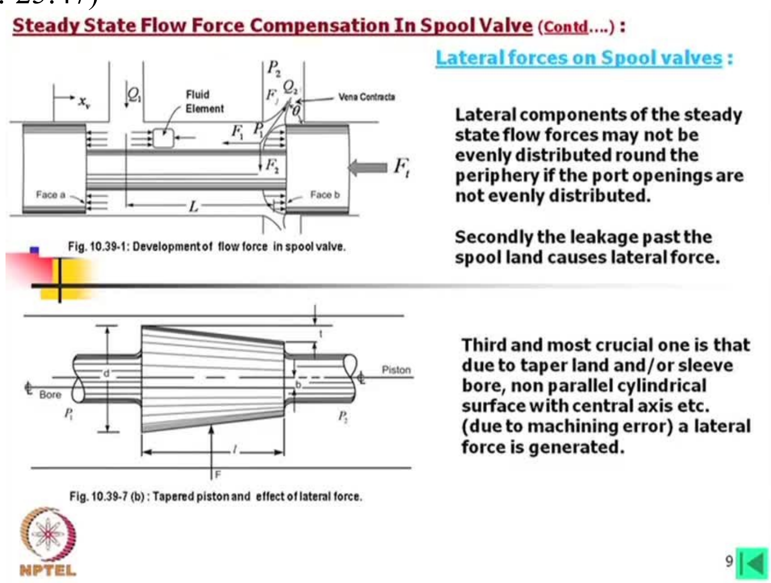

Now apart from this linear force, there is also lateral force on spool valves. Now as I have described, if I consider this force, Z force, then this is having 2 components, F1 and F2. F1 is the flow force which we cannot balance, we have to control, we have to add. We have to control this force by the drive but there is also the lateral force F2 but for the full rectangular port or for the uniformly distributed small rectangular ports or may not be rectangular also, uniformly distributed, if we look into this F2, ideally they are equal and opposite.

So they are cancelling each other. So there is no chance that there will be lateral force. But there may be lateral force due to several reasons. One is that say for example instead of this full rectangular port, we have used say small holes, discrete rectangular holes, they are uniformly distributed. Let us consider at 90 degree but again due to the manufacturing error, there might have they are not exactly opposite to each other.

Two are opposite but they are say for example center through these holes, through holes is not coinciding with the Center of the sleeves. So in that case, there will be an imbalance. This is from that point of view. Again if we consider this cylinder, this cylindrical surface, that cylindrical surface may have several defects. One is that they are not perfect. The surface is not parallel to the axis, some taper is there.

Or the Center of this then center of the spool is shifted. Sleeve, Center of the sleeve and center of the spool is shifted. ? So in that case what will happen? There will be imbalance in this force. This F2 will not be properly balanced. In that case, the spool will try to move towards one side and it will touch the sleeve. And touching the sleeve means we need more force to control. So lateral force we must consider while we are designing the such lateral force.

However, this is we cannot estimate such lateral force because these are due to the manufacturing defects and estimating such manufacturing defects and calculation of lateral force is very difficult. Only experimentally we can find out and we can provide some methods so that this force is also reduced. Now lateral components of the steady-state flow forces may not be evenly distributed round the periphery of the port openings are not evenly distributed.

This is due to the this reason which have already explained. Secondly the leakage past this spool land causes lateral force. Say suppose this is slightly moved in this direction than leakage flow started and that flow is having some lateral force, that will further push the spool in one direction. Thirdly and most crucial one is that due to taper land and/or sleeve bore, bore maybe also tapered, nonparallel cylindrical surface with central axis et cetera and these are due to the manufacturing error, a lateral force is generated. Now how it is generated, we will see in the next slide.

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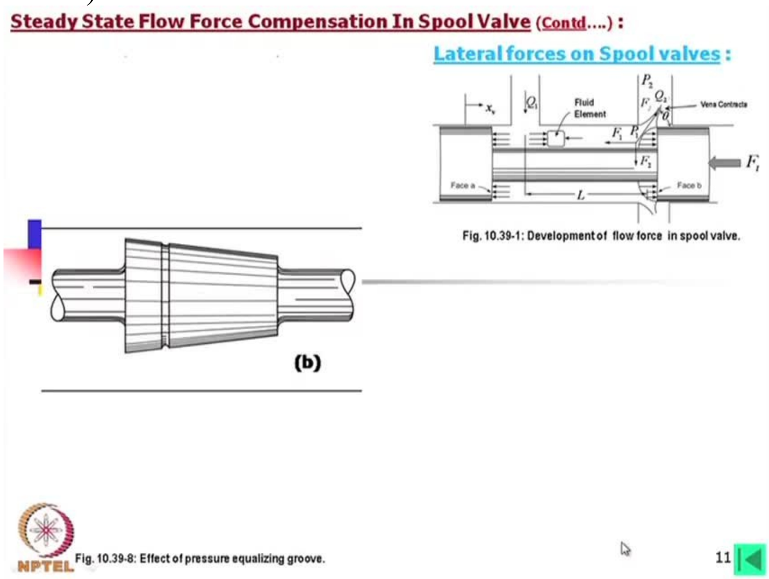

Now this is the ideal one which I have shown. Let us consider this land is like this. Instead of the cylindrical perfection, it is tapered. Of course this is an enlarged view. It will never be like this. But there may have slight taper. Even that will cause substantial lateral force. Now such lateral forces are normally not balanced and push the spool to sleeve. This is obvious.

Now due to taper that what we will have? Say this 1st of all this spool axis is not matching with the bore axis. There might have some suppose let us consider a small amount of lateral force generated due to some reason. After that, what we will find? That if we imagine a ring over the periphery, then here might be the smallest distance, here maybe the largest distance. So in that case, this path of different area or we say varying area over the periphery, in that case if we look into that in case of parallel dirt, if this dirt is parallel, then P1 is P2 is like that, pressure variation will be like that.

If it is a tapered dirt, then pressure variation will be like this. And that definitely you can see that instead of parallel dirt, this will generate a force, you see this due to this nonlinearity. And other side if you look into other side, then this is also some parabolic shape but we can see that there is a difference. Difference is due to that opening area. This means that due to this, there will be definitely a lateral force in this directions okay.

But if it is perfectly parallel, due to this flow, there will be no lateral force. These also not only for spool, this is this happens any piston cylinder. When the spool or piston is moved, additional force is required to overcome internal friction force caused by the lateral push. That is obvious.

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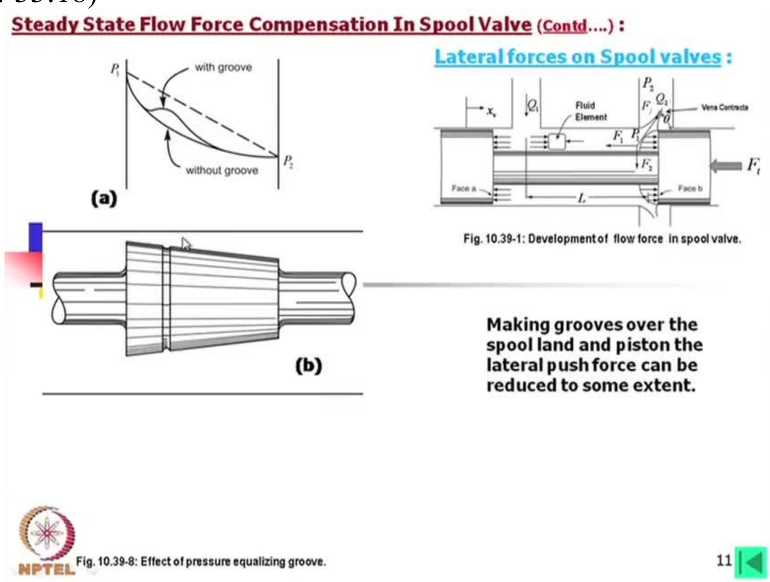

Now how to compensate this? What we can do, we can provide a groove here. Now providing this groove, what happens let us see. Making a groove over the spool land and piston, the lateral push force can be reduced to some extent. How? If we now look into the pressure distribution, due to this groove, this distribution will be something like this. Okay? Due to this, what is happening?

Whatever the pressure here, this is connected to the other side. Say if there is no such groove, but keep in mind this passage what is looking into much much smaller than what we are looking into. This is real sense that will be capillary passage. Because these are this sleeve and this spool, they are very close fit and the difference in diameter maybe only 20-25 microns okay. However, if we make a groove like this, this groove is having a substantial depth maybe 0.5 millimeter or something like that.

This means that this path is directly connected. So throughout this group, the pressure will be same and due to that, this pressure curve will be like this. Say without group, this is the curve pressure distribution and groove, this is the pressure distribution curve. If we look into the other side of this spool, what is there? This side also difference in this pressure distributions. Now here, much I mean larger difference as this deviation was more.

In that case, a little less but ultimately what is happening? If we now estimate at least at that portion, the difference is force is very less. That means, totally the effect is that lateral force is reduced. So this is the method of compensating the lateral force. That is why, you will if you will observe the spool, you will find on this spool there are grooves. This providing such grooves has other problem or merits demerits are there.

Say within this groove, sometimes little dirt particles are accumulated, that gives a problems later. The resultant push force affecting the spool, effect of compensatory pressure equalizing and centering groove et cetera are these grooves. These grooves are called pressure equalizing groove, sometimes that pressure compensation groove, et cetera.

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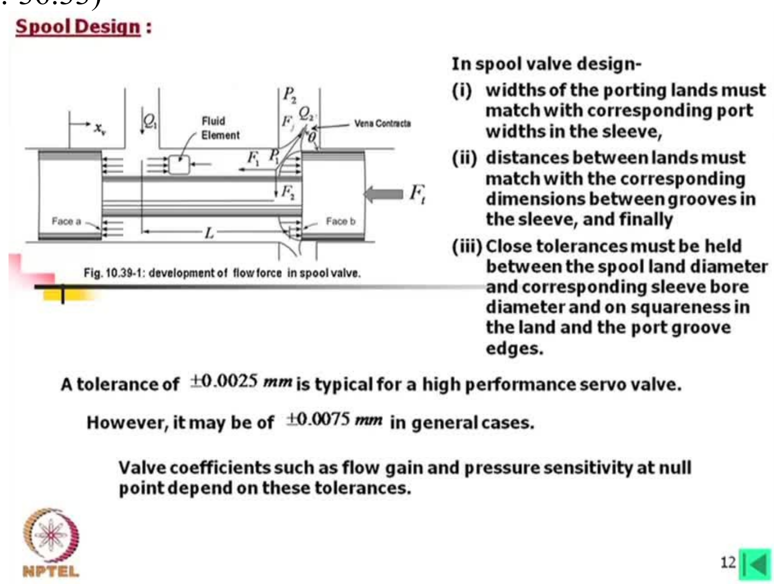

Now in spool valve design, one, with of the porting lands must match with the corresponding port widths in the sleeves. Now importantly, say say for example it is a critical Center valve, in that case, this width must be equal to width of this land. So and critical Center valve is preferred due to the quick response time over the null point. However, maintaining such dimension is always difficult because not only that, but also we have to maintain the distance written.

Say for example, from this point on the sleeve from this point to this point, what is the distance, same distance may have to measure or the proportional distance has to be measured from one inch of the land, the same similar is in the other side. So maintenance of dimension is difficult. However, we have to maintain that for better performance. Distances between lands must match with the corresponding dimensions between grooves in the sleeve and finally close tolerances must be held between the spool land diameter and corresponding sleeve bore diameter and on the squareness in the land and the port groove edge.

Now this is another important factor is that this edges, say from the movement point of view, you may think of that we can provide a jumper here, we can provide a jumper here but if we provide a jumper there, immediately for performance drastically falls. This is because drastically reduces this is because of the reason that in that case, at the time of opening, this Z angle will be different and response will be much poorer.

Then if we can maintain the surface, maintaining the such surface at the opening there will be the turbulent flow. But that turbulent flow is preferred from the response point of view. If however if this edges are very sharp, in that case, there is a problem that due to this lateral force, it may get struck there. So to avoid that, there is a small the breaking of such edge is done. That means, you may find, if it is measured, a small not samper, you can say is round off is done at these corners. Okay?

However it is better to keep these edges as sharp as possible. A tolerance of as you can see 0.0025 millimeter. Look at the tolerance, this 0.25 millimeter is typical for a high-performance servo valve. You see, this to get this tolerance, not only this dimension control but also the surface finish is required. So you can imagine how accurate machining is required. However, I had maybe plus minus 0075 millimeter in general case. Say little lower performance, low performance valve or maybe general-purpose valve.

But these are for very accurate position control or or velocity control. Valve coefficients such as flow, gain and pressure sensitivity at null point depend on these tolerances.

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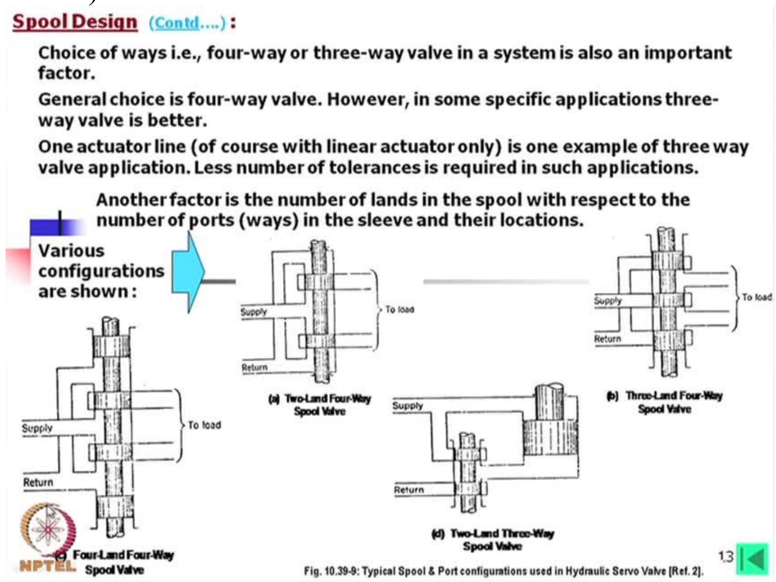

Now choice of ways, this is what is way? Say if I say that 4 by 3 DC valve, that means 4 port 3 position or 3-way valves, so that is called way. Now no 3 4 port 3 position, that means 4 way 3 position valve. 1st one is the number of port or way and 2nd one is the position but here, the way means that port or the how many directions the flow occurs. So how to select or I would say that where it should be 4 way or 3 way or 2 way, that is an important factor we have to according to requirements, we have to make a choice of that.

Now general choice is four way valves because four way valve is it is easy to think of the system as well as maybe for from controller point of view. However, this with the number of ways, the cost also increases. Now in some specific applications, three-way valve is better. One actuator line of course with linear actuator only is one example of three-way valve application. Less number of tolerance is required in such applications.

Say with the linear actuator and with three-way valve, the system becomes simple, compact and relatively it is also considerable. So where we are moving this actuator frequently in opposite direction, then two-way valve is a good choice. Another factor is the number of land in the spool with respect to the number of ports that is ways in the sleeves and their locations. You see, this I will show that four way may have 3 lands, may have four lands or may have two lands also.

So it can be made like this but they have own merits and demerits which I shall discuss. Now various configurations as shown are possible. 1st, let us consider the 2 land 4 way spool valve.

This is 2 land but there are 4 way. What are the 4 way? If we see that this is the supply flow, let us consider this is a critical center or even if we overlap valve but still, when it is in neutral position, this it is totally closed, it cannot go in any directions, this flow. So that means flow is being bypassed through the relief valve maybe.

Now if we move in this directions, then oil will be supplied through this and this will go one end of the actuator and the from the other end, this oil will return back to tank. If I move in the opposite directions, it should be vice versa. Okay? So this is one configurations. Now if you look into the other, this is 3 land, 4 way spool valve. In that case, what is happening?

Here, the oil is directly coming to inside the valve, inside this this spool stem and it can move in either directions but if we consider this valve, so this when we are moving in this directions the oil is going like this and the return oil is going back through this path okay? And if I move in the opposite direction, this will be opposite. Now there is a question that why we should go for this? We can make, this is a very simple but we will see that these 2 is having some differences also, merits and demerits.

However, the another valve is that the 2 land 3-way valve that is with actuator but before that we will also see another valve. That is if we say this is again four way but we have 4 land. We can say, apart from these 2 land, there are another 2 land through which the oil is going back okay? So starting from this one, this is the 2 land, this is 3 land, this is 4 land but all are 4 way. So which one we should choose and why? If we can do the same job with this valve, why we should go for 4 land or 3 land okay?

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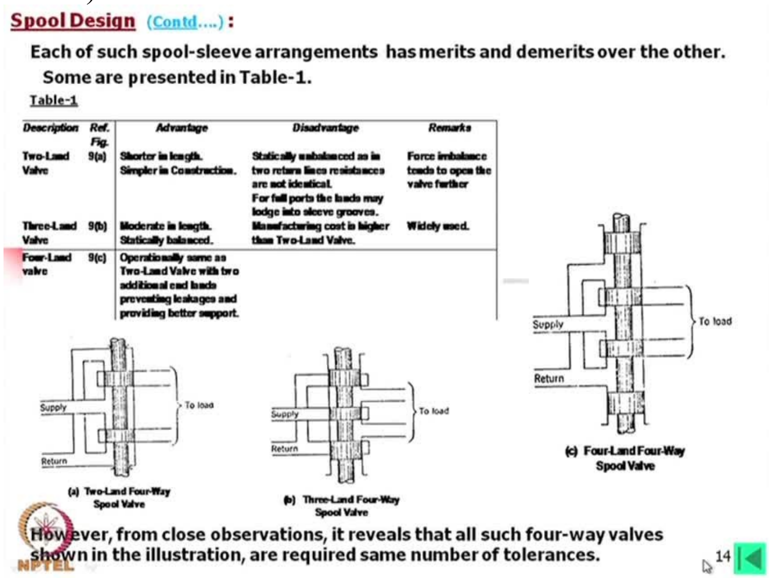

Each of such spool-sleeves arrangements has merits and demerits over the other. Now if we look into that, such merits and demerits, then 1st of all if we consider 2 land valve, that is two lands four way, this is shorter in length, simpler in construction, statically unbalanced as in 2 return lines, resistances are not identical. For full port, lands may lodge into the sleeve grooves, say in this case, say for critical center, it might happen you can see that this simply can go inside.

Say this is a full rectangular port okay? Now this sleeve height or width whatever we call it, is exactly, ideally is equal to the groove width. So in that case for full port, simply this can go inside. And also when it opens, we can see the some unbalanced force. Now remarks, force imbalance tend to open the valve further in this case. So stability even at null point, it is difficult.

Now if I consider the other one, that means which is has having the 3 land, moderate in length, statically balanced, this is statically balanced. Say if we look into this, this will not try to move this or that way because this path is closed. And these are widely used. Now if I consider the other one, that is the last one, that is the 4 land and 4 way, then operationally same as 2 land valve with 2 additional end lands preventing leakage and providing better support.

So if we had to compare, then we can compare this one with this. In that case also, this is open. Directly flow is coming to the spool. So this unbalance will be there but as there is a land support, there is no chance it will go into the groove and also, there will be the leakage will be less. In that case, this directly this is open to the I mean outside and the leakage has to depend only on this sealing. In that case, this path and then sealing, okay?

So operationally these 2 are same but this has much better performance whereas this is slightly different configuration. Moreover, from close observation, it reveals that also is four way valve shown in the illustrations are required same number of tolerances. That means tolerances means say this width, so maintaining such width and this length, here this length, in relation to this length, all has to relate with close tolerances.

So that means if we think in terms of tolerances, it will be same for both but obviously, this will be more expensive than this one.

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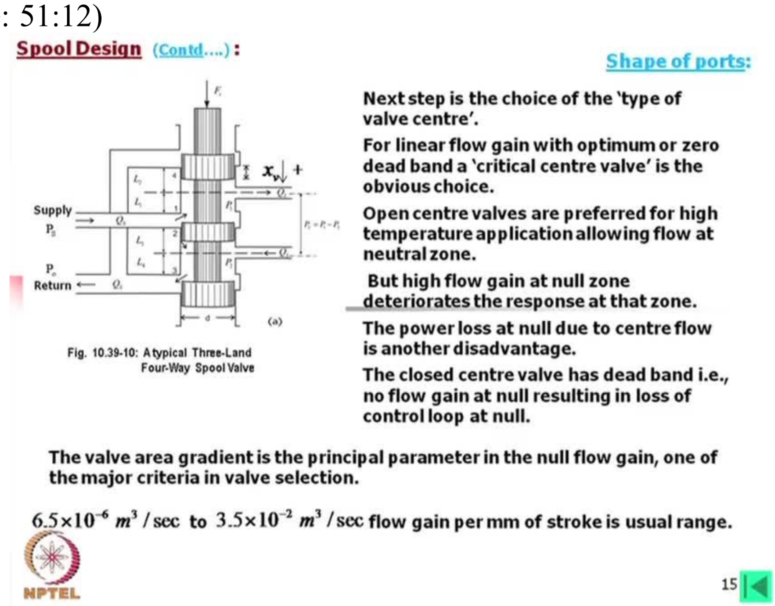

Now next step is the choice of the type of valve Center. That means valve Center means that is a closed Center, open Center or critical center. For linear flow gain with optimum or zero dead band a critical center valve is the obvious choice. Open Center valves are preferred for high-temperature applications allowing flow at neutral zone. You see, if we prefer that there is a high-temperature and that temperature to be cooled, in that case it is better to keep this center open at null positions.

But the problem is that for quick action, that means if we one we give a stroke, the response will be delayed due to that and in many cases, it is not tolerable, it is not acceptable but high flow gain at null zone deteriorates the response at that zone which I have mentioned just now. The power loss at null due to the Center flow is another disadvantage. The closed Center valve has dead band, no flow gain at null resulting in loss of control loop at null.

The valve area gradient is the principle parameter in the null flow gain, one of the major criteria in valve selection. Now I have given some also practical data, the it is 6.5 10 the power minus 6 meter cube per second, that is it is 6.5 cc and to 3.5 to 10 to the power minus 2, that is the T5 3.5 litre perhaps per second. flow gain per millimeter of stroke is usual range. The spool diameter is selected accordingly okay.

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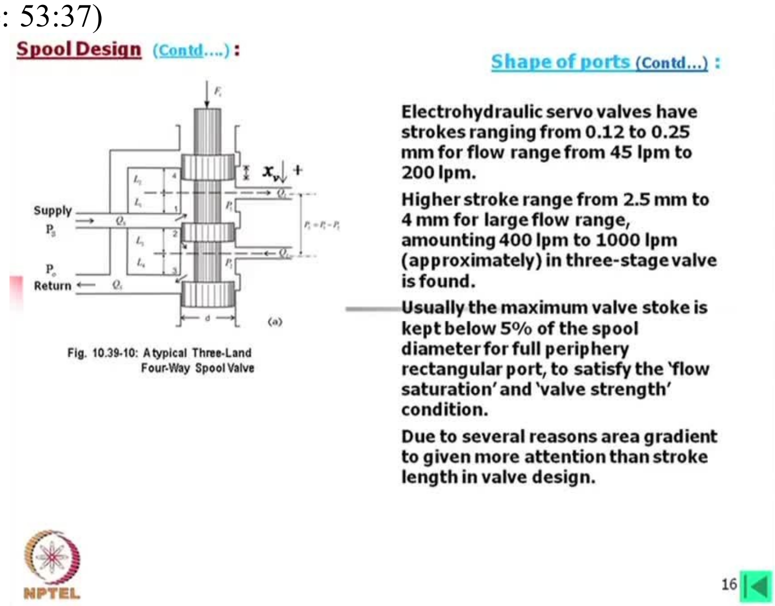

Electrohydraulic valves have stroke ranging from 0.12 to 0.25 millimeter. Just imagine how small it is, 0.25 millimeter, one fourth of a millimeter and maybe very large stroke to 45 litre per minute to 200 litre per minute. You just imagine the orifice size, it even if rectangular port, say diameter maybe 10 to 25 millimeter and width 0.25, such a small hole but flow is 45 to 200 litre per minute. Higher/range from 2.5 millimeter to 4 millimeter for large flow range, amounting 400 litre per minute to 1000 litre per minute approximately in 3 stage valve is found.

That that is 3 stage valve you see this pilot stage, then one main stage, that main stage is operating the another main stage. You can see this is for very high flow okay. Usually the maximum valve stroke is kept below 5 percent of the spool diameter for full periphery rectangular port to satisfied the flow saturation and valve strength condition. This we should say that flow saturations means that I would say that with the stroke, the flow is increasing but we have to consider that too much nonlinearity should not be there.

So from that point of view, the flow saturations and also the valve strength is the iBook called the how much is the strength is required to move this spool perhaps. Due to several reasons, area gradient is given more attention than stroke length in valve design. Now area gradient is the what is called pi D is called area gradient. That is more important than the stroke length. That means that decides what should be the diameter of the spools.

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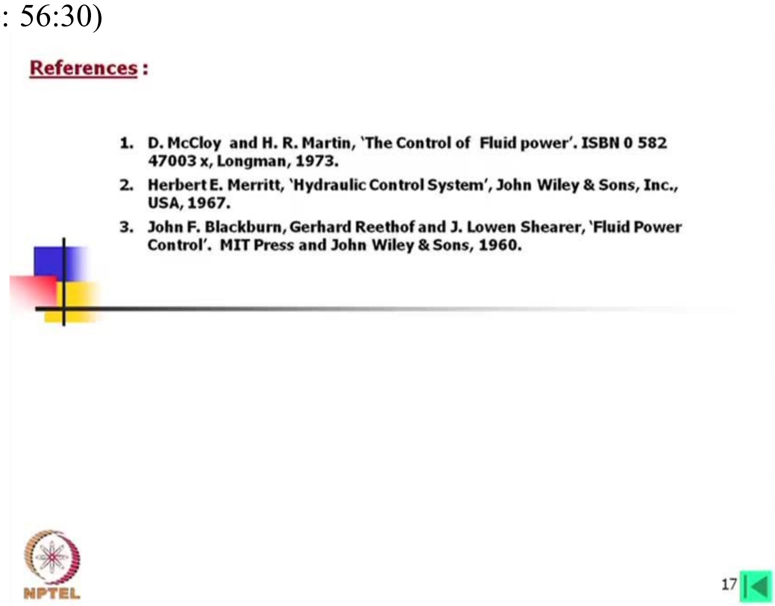

And we have followed this mainly I would say the hydraulic control system by Merritt, that book we have followed. As well from to know, we have for better knowledge you can follow also Martin and McCloy, particularly the orifice sizes it is much discussed in detail and also, in general terms if you have more idea about the valves and their applications, et cetera, you can follow this Blackburn Reethof also. However the mostly I have consulted the Merritt's, Hydraulic control system. Thank you.