ABSTRACT

High frequency valves can be realized when the required stroking forces and displacements of the valving elements, whether poppets or spools, are minimized to cope with the capabilities of compact actuating devices. A new class of valves are proposed and analyzed in this work, in which the valving elements are subjected to the high inlet pressure at both sides that have small area difference. This would result in reducing both the required driving forces and the strength needs of the valving elements. The valving element return to its initial position in this case results from the pressure and flow forces unbalance only, or with additional assistance of a spring force. The proposed large control edge length allows obtaining appreciable large control orifice area from a small valving element displacement, and hence high flow gain. The small valving element displacement reduces the dynamic forces, the demands on the actuating devices and allows the use of piezoelectric actuators of short stroke, magnified when required, or the electromagnetic driving devices that generate high forces at narrow gaps and reasonable ampere-turn values. The configurations of the fast switching valves well fit the purpose of Pulse Width Modulation control techniques. Examples of using the proposed valves as 3/2 and 2/2 directional control valves of size NG 6 are shown and the flow gain and forces acting on the valving elements are numerically evaluated. The concept is applicable for larger sizes. The flow gain is comparable with conventional directional control valves of similar size. Four 2/2 valves can be assembled in one housing to control the connections between the two load ports and the pressure and tank ports independently for highest efficiency and minimum number of control pulses. As pilot valves, they provide a low cost technique for upgrading conventional valves to fast switching valves. If controlled by a proportional electromagnetic device or an adjustable spring, the valve can be designed to operate as a relief or a reducing valve.

KEYWORDS: Fast switching, hydraulic, valve, directional control, pressure control
1. INTRODUCTION

Fast switching valves with high flow rate gain are key components in modern digital hydraulics applications. The valving elements in this type of valves should be of small mass and have relatively small displacements to be actuated by short stroke fast response actuators, such as piezoelectric actuators or electromagnetic device of narrow gap and high force. The valve design should be developed so as to allow high flow rates in spite of the valving element limited stroke.

A piloted seat type fast switching valve utilizing the Horbiger plate concept had been presented in [1]. Another design having a 3/2 solenoid operated directional control valve as the pilot stage, which drives the main stage consisting of multiple poppet valves, has been presented in [2]. The switching times of these valves are generally less than 5 ms and the nominal flow rates attain up to 100 l/min. A piezo stack actuator had been utilized in [3] to actuate a fast switching high flow rate directional control valve. Kudzma et al. [4] presented a servo valve driven 3/2 spool valve with multi metering edges, which have a switching time less than 1 ms and a flow rate amounting to 65 l/min at 1.5 MPa pressure drop. Elgamil et al. [5] showed that a servovalve with a two land spool can be operated stably when the pilot stage is of the closed center type, and they theoretically determined the flow forces acting on the spool in this case. Elgamil et al. [6], and on the basis of the analysis and results of [5], presented and theoretically analyzed some performance aspects of a proposed two stage fast switching directional control valve in which two 3/2 piezo stack actuated poppet valves are used in the pilot stage to drive the spool of the valve main stage. Valves of this type with two or four land spools were theoretically verified to operate satisfactorily, and would have a speed of response exceeding that of a servo valve of the same size. Elgamil [7] described the details of a new type of fast switching high flow gain valves, suitable for different control functions in hydraulic systems. In this paper some design details for this valve are proposed and the valve static characteristics are theoretically analyzed.

2. VALVE DESCRIPTION

The main forces acting on the valving element of a valve, which have to be overcome by any actuator, are pressure, flow, inertia, and friction forces. Strength and rigidity in addition to these forces should be considered during the valve design stage.

2.1. Poppet valve configuration

Figure 1 shows a layout for a novel poppet valve design in a 2/2 configuration that takes these factors into account. The poppet (2) is inserted in the valve housing (1), and is acted upon by a closing pressure force equal to the pressure p times the small area (4). The ports (P) and (A) are consequently closed hermically with a force that increases with the increase of the pressure p. A spring (3) can be added for closing the connection
hermetically if the pressure $p$ is low, and would help in increasing the valve closing speed. For connecting the ports (P) and (A), a force $f$ is to be applied to the poppet to displace it a distance $x$. The required force component to overcome the pressure force would consequently be small since the area (4) can be made as small as required by the strength considerations.

![Diagram of a 2/2 poppet valve](image1)

*Figure 1. Layout for a 2/2 poppet valve*

Figure 2 shows an example for the poppet (2) and its surroundings. In this arrangement a pusher (5) is guided inside a sleeve (6) to enable the poppet (4) to be floating so as to adjust itself when seated.

Besides, it allows for adding another port for the valve if required. The large poppet diameter allows a small poppet displacement to generate large control orifice area. This short poppet stroke well suits capabilities of powerful actuators that generate high forces at small gaps. Pressure control actions (relief or reducing) can be achieved through the proper connections of the valve ports. The control of pressure can be realized by electric actuators as in proportional pressure control valves, or through spring loading.

![Diagram of a 2/2 poppet valve](image2)

*Figure 2. Main parts of a proposed 2/2 poppet valve*

Figure 3 shows designs and symbols for fast switching directional control valves composed of either two 3/2 poppet valves or four 2/2 valves of this configuration, assembled in one housing. The symbols shown are for electrically operated valves. The poppet and spool are designed so as to reduce their share in carrying the reacting force resulting from diverting the flow direction and hence reduce the actuating force demand.
These designs allow precise control by fast switching PWM signals, and allow also decoupling of the load ports. Compared with servo and proportional valves used for precise control of actuators, PWM directional control valves would render also precise control, reduce costs, and improve efficiency. Further, decoupling the load ports control improves the controllability and reduces the number of the required control pulses and in some cases components.

2.2 Spool valve configuration

Figure 4 shows a proposed design in which the poppets are replaced by spools.

This design avoids the shocks of the poppet on its seats. With these fast switching valves, production costs are considerably reduced since the accurate matchings of the
several control edges required in servo and proportional valves are avoided. The spool initial position can simply be altered using the threaded part (7) to adjust the required match of the two only control edges. Contrary to the poppet which is split into two parts; namely a pusher and a poppet, all the spool lands are integrated in one piece.

3. FLOW RATES AND VALVING ELEMENT FORCES

Ansys-Fluent software package has been used to determine the pressure and flow distributions inside the valve, as well as the valve flow rates and the forces acting on the valving elements, for poppet and spool valves of nominal size NG 6. The poppet and the spool diameters were taken equal to 13 mm during the analysis, and the unbalanced area diameter was 3 mm. The mass of these elements is about 0.025 kg and they have small displacements, which would result in sensible reduction in their inertia forces. A 3-D model has been adopted assuming that the oil density and viscosity are 860 kg/m$^3$ and 0.03 Ns/m$^2$ respectively. Standard wall function is selected in FLUENT for modeling the near wall boundary layer.

The mesh type is “tetrahedral cells”, and the number of mesh cells is about 175,000 for the poppet valve and 198,000 for the spool valve. It is worth mentioning that increasing the number of cells to one million rendered only about one percent change in the results. The boundary conditions are “pressure inlet ranging from 10 bar to 200 bar and pressure outlet equals 0 bar - wall conditions elsewhere”, the convergence criteria is “solution residuals < 10$^{-5}$”, and the turbulence model is “realizable k-epsilon”.

3.1 Poppet valve

Figure 5 shows the domain of analysis for the flow from the high pressure port to the low pressure one for the two 3/2 poppet valve. It shows also the resulting pressure and velocity distributions within the domain at full control orifice opening of 0.5 mm, when the pressure difference between the inlet and outlet ports is 10 bar. This analysis is also applicable for the 2/2 valve since it has the same domain.
The maximum flow velocity is seen to be 28 m/s and occurs locally at the control orifice, and the velocity reaches about 10 m/s when passing through the poppet. Passing through the poppet imposes about 1 bar pressure drop across it, which leads to about 11 N undesired extra closing force. This force, which increases with the flow rate increase, can be significantly reduced by bypassing the majority of the flow in a parallel path away from the poppet inside path. This solution might lead to the increase of the valve dimensions because the selected valve of size NG 6 can hardly accommodate all the required paths inside its small housing.

Figure 6 shows the variation of the valve flow rate with the variation of the pressure drop between the inlet and outlet ports (P to A or P to B) at various control orifice openings.

![Figure 6. Flow rate vs pressure drop at various poppet displacements](image)

Keeping in mind that this pressure drop is calculated per one control edge only, this valve would replace a servovalve of size NG 10, with higher efficiency and speed of response and lower cost. If one control edge is kept fully opened while modulating the other one, the system efficiency would furtherly and evidently increase.

Figure 7 shows the variation of the combined flow and pressure forces acting on the poppet with the variation of the pressure drop between the inlet and outlet ports at various control orifice openings. It is to be noted that these forces are of a closing nature.

![Figure 7. Flow and pressure forces vs pressure drop at various poppet displacements](image)
At the selected maximum opening of 0.5 mm, the closing force acting on the poppet is 15 N when the pressure drop is 10 bar, and 302 N when the pressure drop is 200 bar. These forces are manageable by piezoelectric or electromagnetic actuators. A CFD study for the case of connecting the ports (A) and (T) in the upper part of Figure 3.b, where the flow passing through the poppet is avoided, has been carried out. The analysis showed in this case that the flow rates are kept the same but the forces are drastically reduced, at 0.5 mm opening, to 1.6 N at 10 bar pressure drop and 38 N at 200 bar pressure drop as shown by the dotted line in Figure 7. This arrangement for connecting a high pressure port to a low pressure one can be applied to all connections, but on the account of increasing the number of passages in valve body and the valve dimensions.

The pressure considered during this analysis is the pressure drop between the inlet and outlet ports. However, the value of inlet pressure should be taken into account when calculating the force acting on the poppet. For example, if the inlet pressure is 300 bar and the load pressure at port (A) is 100 bar, the pressure drop is 200 bar. The 100 bar pressure difference applied to the unbalanced area (4), of 3 mm diameter, adds 70 N closing force.

The flow rates from the port (A) or the port (B) to the port (T) in case of 3/2 valves are of the same order, and the pressure and flow forces are small and ensure keeping the connections opened.

3.2 Spool valve

Figure 8 shows the domain of analysis for the flow from the high pressure port to the low pressure one for the two 3/2 spool valve, and the resulting pressure and velocity distributions within the domain, when the pressure difference between the inlet and outlet ports is 10 bar, at 0.5 mm control orifice opening. This analysis is also applicable for the 2/2 valve since it has the same domain.

![Image of analysis results](image)

*a. The domain  b. Pressure distribution  c. Velocity distribution*

*Figure 8. The CFD simulation results of the spool*

Figure 9 shows the variation of the valve flow rate with the variation of the pressure drop between the inlet and outlet ports (P to A or P to B) at various control orifice openings.
Figure 9. Flow rate vs pressure drop at various spool displacements

Figure 10 shows the variation of the combined flow and pressure forces acting on the spool with the variation of the pressure drop between the inlet and outlet ports at various control orifice openings. It is to be noted that these forces are of a closing nature.

It can be seen that the flow gain and the combined flow and pressure forces are slightly larger in this case than those of the poppet type. Except for the absence of seat shocks present in poppet valves, all the analysis mentioned in 3.1 for the poppet valves is applicable in the case of spool valves.

Figure 10. Flow and pressure forces vs pressure drop at various spool displacements

4. CONCLUSIONS

Configurations and some design features of new fast switching valves that can be used for directional or pressure control purposes are presented. The presented valving elements, whether poppets or spools, are close to be hydrostatically balanced in order to reduce the stroking force and strength requirements. The large diameters of the valving elements, which are of small masses, result in obtaining high flow gains at small displacements. The valving elements short displacements and small masses reduce the inertial dynamic forces and allow using actuators of small strokes and strong forces at small gaps. Flow diverting reaction forces on moving parts, and induced forces due to the flow through these parts are studied in order to minimize the flow forces. CFD simulations have been carried out to obtain the pressure and velocity distributions within
poppet and spool valves, and to calculate the flow rates and the forces acting on the moving elements. The study shows that the values of the valving elements stroking forces suit the capabilities of the piezoelectric actuators as well as the electromagnetic actuators of small gaps. The CFD analysis showed also that smaller actuators can be used when the flow passing through the valving elements is avoided. The resulting flow gains show that the studied NG 6 valve can replace a larger NG 10 servovalve, with a higher speed of response. Decoupling the ports connection control, the absence of pilot stage, and the absence of the need to match the control edges make these valves replacing servovalves of larger size not only with higher speed of response, but also with lower cost and larger efficiency.

5. ACKNOWLEDGMENTS

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REFERENCES


