Experimental and Theoretical Investigation of an Interlocked spools Flow Divider

M. Metwally, A. Abou El-Azm Aly and I. El-Sherief
M.T.C., Cairo, Egypt

Abstract

Flow divider / combiner valve divides / combines flow in a predetermined ratio regardless of the load pressures at the outlet ports. It is used to synchronize the movements of hydraulic actuators under adverse conditions. There are two types of flow divider/combiners, sliding spool and rotary (usually gear), where each type has its own set of performance characteristics such as flow range, pressure capability, accuracy and application parameters.

In the present work, a mathematical model for interlocked spools of a cartridge design flow divider valve has been carried out to study static and dynamic characteristics of the flow divider valve at different load pressures. The model has been verified by direct comparisons with the experimental results. Comparison between the interlocked (split) spool and a single spool sliding flow divider has been performed.

The comparison between experimental and simulated model for the interlocked flow divider has showed a good agreement for the studied system pressures up to 50 bars to validate the theoretical model results. Theoretical comparison has been performed between the interlocked split spool and the single spool flow divider performances parameter. It has been found that the interlocked split flow divider has a low inertia effect which enhanced valve response at the studied load pressure regimes.

1. Introduction

Sliding spool flow divider / combiner valves are used to proportion the flow from a single source into two actuators. In the reverse mode, the valve takes the flow from the two proportion sources and combines it into one flow.

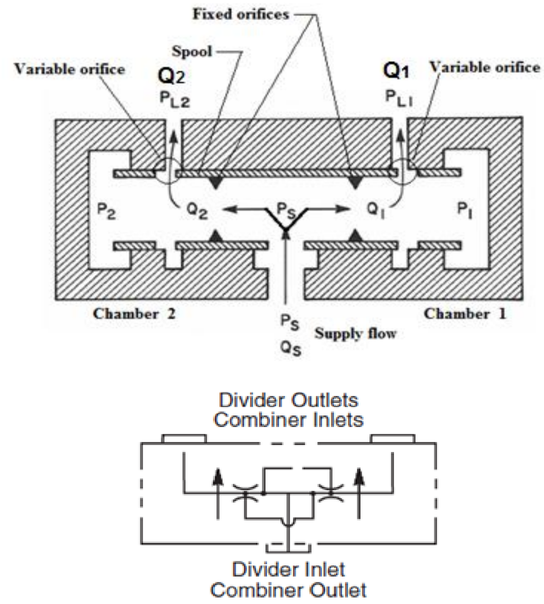


Figure.1. Sliding single spool flow divider/combiner valve.

A schematic drawing of a spool type flow divider is shown in Fig. 1. If the flow through one orifice increases, an increased pressure drop results and a spool reduces the orifice, equalizing the flows. Should one of the output ports be blocked, the pressure drop becomes zero and a spool moves to completely close the other outlet port.

Over the past years, industrial manufacturing companies and researchers have tried to develop flow divider valves of high precision and high response independent of the system loading conditions. This problem has been the subject of several research studies at the University of Saskatchewan, Canada [1-11]. Innovative designs [1, 3, 5, 6, and 7] have resulted in great improvements in this area, but usually a complicated and hence, costly valve has resulted. As the complexity of any design increases, its sensitivity to fluid contaminants increases, reducing its reliability. In their analytical studies it was demonstrated that the prime source of error could be attributed to flow reaction and friction forces. These results were based quantitatively from experimental data on the various models that each researcher was investigated.

Cheng [12] simulated the steady and dynamic performances of a flow divider valve numerically by solving the characteristic equations. The simulation results show that flow force is the key factor to affect the flow division accuracy. In addition results show that increasing load pressure differential, spool mass, and metering orifice area will enhance the oscillatory tendency and increase the valve settling time.

The flow divider valve in the current study, as shown in Fig. 2, is of interlocked spool type. When flow enters the divider inlet port, it will pass through orifices in each of the interlocked spools. The flow passing through the orifices creates a pressure drop which pulls the two spools away from each other.

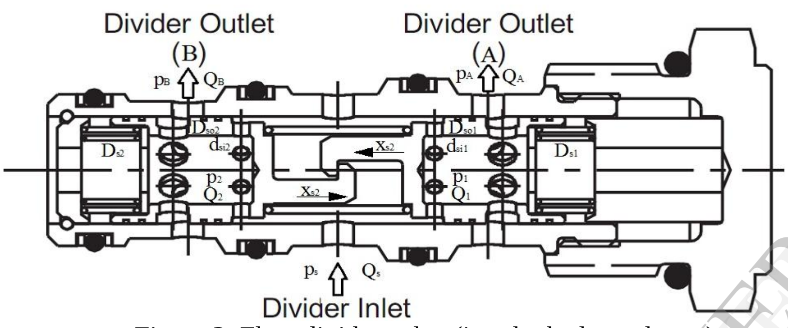


Figure.2. Flow divider valve (interlocked spool type).

The pressure drop across the orifices pulls the two spools together. The combined flow then passes through the combiner outlet.

The flow then passes to the two divider outlet ports. The division of flow (i.e. 50-50, 60-40, 66-33, etc.) is determined by the orifice sizes in the two spools. When flow is being combined, it enters the valve through two combiner inlets.

In this paper an experimental and theoretical investigations of the interlocked spool type flow divider valve will be introduce to study the valve behaviour at different load pressures. The valve mathematical model is simulated using SIMULINK to investigate its static and dynamic characteristics and experimental setup is established to validate the static results from simulation of the mathematical model. A theoretical comparison between the single and interlocked spool flow dividers has been performed to compare between their performances.

2. Experimental Setup

The experimental test rig has been set up in the Hydraulic laboratory at the Mechanical Power and Energy Department in Military Technical College. The test rig has been established on hydraulic bench equipped with all accessories and hydraulic components needed to build the required circuits. The conducted experiment is shown in Fig. 3.

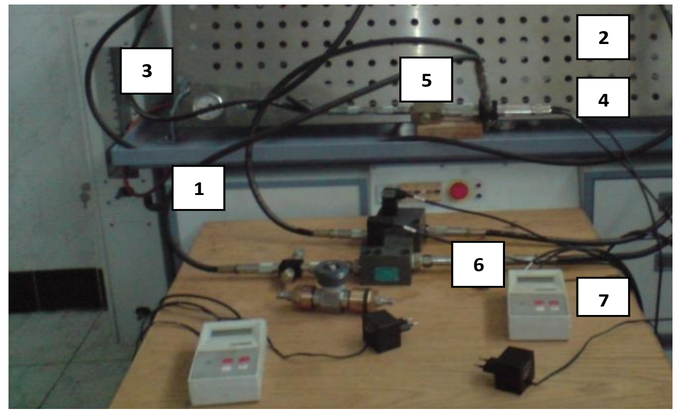


Figure.3. Experimental set up; (1) power pack unit, (hydraulic bench, (3) inlet control valve, (4) pressure transducer, (5) flow divider, (6) digital flow metre, (flow meter readout.

The main measured parameters of the hydraulic circuit are the input pressure, flow rate to the flow divider valve and the output pressure and flow rates of the flow divider ports. The instrumentations used are pressure transducers (4) of the range 100 bars and digital flow meter (6). The instrumentations have been calibrated to find out the scale of the volt corresponding to measured value; pressure and flow rate. The transducer has been also connected to a readout unit which is connected to a data acquisition USB unit to store the measuring data over the sampling time. The measuring time was very short that the temperature could be assumed to be constant during the measuring intervals.

3. Modeling and simulation of the flow divider

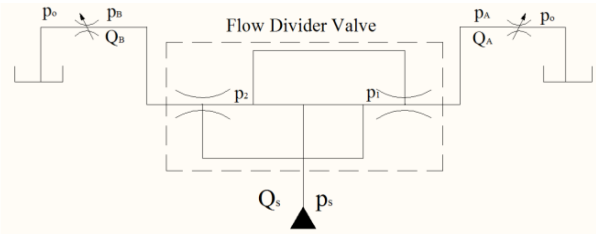


Figure 4. Split spool flow divider circuit

To simplify the mathematical model of the valve the following assumptions have been taken into consideration; since orifices are in parallel, flow rate through both of them are equal to the inlet flow rate, thus $Q_s = Q_A + Q_B$. The pump delivers constant flow rate with oil density, viscosity and bulk modulus of constant values and the return line pressure is the atmospheric pressure.

The flow rate equations for flow divider

The flow rate through the flow divider orifices, Q_1 and Q_2, could be related to the supply flow rate as follows:

$$Q_1 = C_d\, A_{i1} \sqrt{\frac{2}{\rho}(p_s - p_1)} \tag{1}$$

$$Q_2 = C_d\, A_{i2} \sqrt{\frac{2}{\rho}(p_s - p_2)} \tag{2}$$

$$Q_s = Q_1 + Q_2 \tag{3}$$

where A_{i1} and A_{i2} are inlet flow divider orifices area, p_s is supply pressure, p_1 and p_2 are the flow divider spools side orifices pressures. C_d is the discharge coefficient for the flow through orifice and has been taken to be constant with a value of 0.61, while ρ is the oil fluid density of 850 kg/m^3.

The flow rate equations at flow divider outlet:

$$Q_A = C_d\, A_{o1} \sqrt{\frac{2}{\rho}(p_1 - p_A)} \tag{4}$$

$$A_{o1} = f\,(x_{s1} + x_{s1o}) \tag{5}$$

$$Q_B = C_d\, A_{o2} \sqrt{\frac{2}{\rho}(p_2 - p_B)} \tag{6}$$

$$A_{o2} = f\,(x_{s2} + x_{s2o}) \tag{7}$$

where A_{o1} and A_{o2} are the outlet flow divider variable orifices areas which are function of the valve spools displacement; x_{s1} and x_{s2}. x_{s1o} and x_{s2o} are the initial valve outlet spool opening due to valve springs effect. p_A and p_B are the flow divider outlet pressure at port A and port B respectively which are function of the load pressure. The pressure building up inside the valve spool due to the flow inlet and outlet of the valve spools could be deduced by the continuity equations as follows:

$$Q_1 - Q_A - A_{s1}\,\dot{x}_{s1} - \frac{V_{os1} + A_{s1}\,x_{s1}}{B}\,\frac{dp_1}{dt} = 0 \tag{8}$$

$$Q_2 - Q_B - A_{s2}\,\dot{x}_{s2} - \frac{V_{os2} + A_{s2}\,x_{s2}}{B}\,\frac{dp_2}{dt} = 0 \tag{9}$$

where A_{s1} and A_{s2} are the flow divider valve spool cross sectional areas. V_{os1} and V_{os2} are the flow divider valve spool initial cavity volume. The variables $\dot{x}_{s1}$ and $\dot{x}_{s1}$ are the flow divider spool displacement variation with time.

Interlocked spool flow divider valve equation of motion

The spool displacement is controlled by the pressure difference of the internal pressures which was found by balancing the forces acting on the spool. The forces balance on the valve spool is, shown in Fig. 4:

$$(p_1 - p_s)A_{s1} = -m_{s1}\ddot{x}_{s1} + C_3\dot{x}_{s2} - (C_1 + C_3)\,\dot{x}_{s1} + k_3\,x_{s2} - (\tag{10}$$

$$(p_2 - p_s)A_{s2} = m_{s2}\ddot{x}_{s2} - C_3\dot{x}_{s1} + (C_2 + C_3)\,\dot{x}_{s2} + k_3\,x_{s1} + (k_2 + k_3)x_{s1} \tag{11}$$

where m_{s1} and m_{s2} are the mass of the two spools.

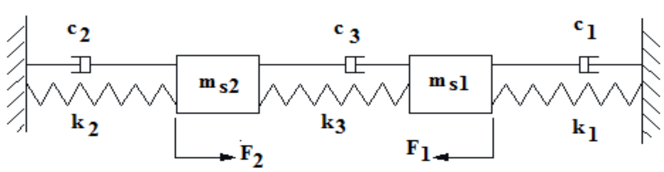


Figure 4: Equivalent flow divider mass spring dumper system

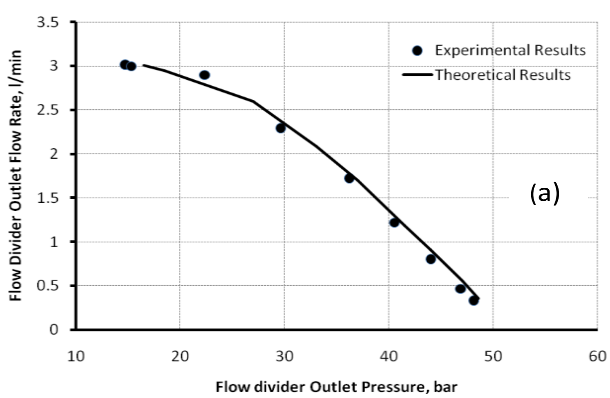
4. Results and Discussions

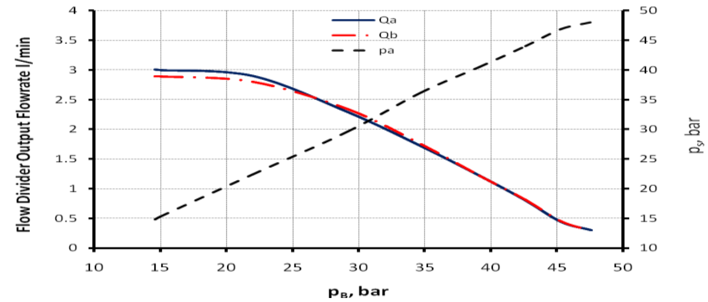
The results for flow divider performance have been illustrated as static and dynamic characteristics. The pressures and flow rates through each of the inlet and outlet flow divider ports have been measured experimentally and compared with the numerical simulation.

Static characteristics of the flow divider valve

The static characteristics of the flow divider have been plotted for experiment and simulation results. Figure 5, presents comparison between the experimental results and the simulation results for the flow rate vs. load pressure variation of the flow divider up to 50 bar. The increase of the load pressure has a significant effect on the flow divider valve static characteristics. It has been shown that the simulation results have a good agreement with that from the experimental results in the range of load pressure up to 50 bar.

In Fig. 6, the difference between the flow divider outlets ports as a function of the load pressure have been illustrated. It has been shown that as the load pressure increase the difference between the outlets two ports have been reduced up to the value of 40 bars where the difference became zero. The error percent between the outlet two ports from the flow divider valve has a maximum value of 4% at a load pressure of 15 bars, as shown in Fig. 7. This may highlight that this valve should be used in loads larger than 15 bars, it has low sensitivity at low pressure, and the dominant working range for this valve is around 30 to 50 bar where the error is reduced.





(b)

Figure.5. (a) Experimental and theoretical results for the flow divider outlet pressure versus the outlet flow rate, (b) Effect of the flow divider output load pressure p_b on the output flow rate and supply pressure p_s.

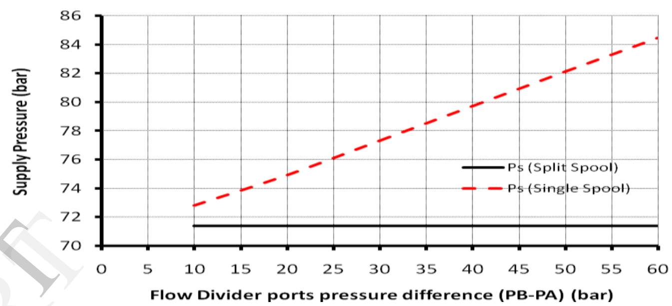


Figure.6. Comparison between single and split spool flow dividers output ports pressure difference on the hydraulic circuit.

Dynamic characteristics of the flow divider valve

The dynamic characteristics of the flow divider spools displacements and outlet flow rates as function of the load pressure have been plotted in Fig. 8 to 11. In Fig. 8, the dynamic responses of the two spools displacements, spool 1 and spool 2, for different load pressures have been plotted, but the load pressures are equal at the two flow divider outlet ports.

It has been shown that with the increase of the load pressure, the response time of the spools increased and this increase in not equal in the two spools which means that the flow divider dynamic response reduces as the load pressure increase.

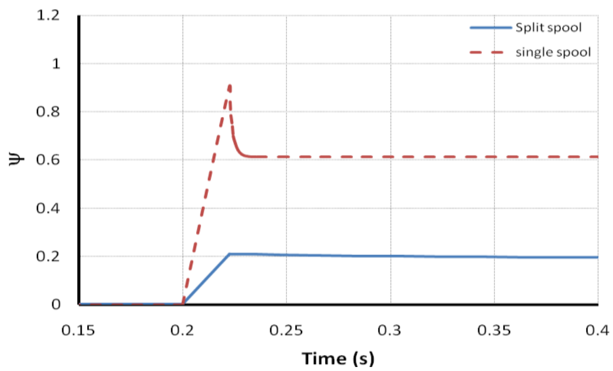


Figure.8. Dynamic response comparison of the flow coefficient between the split spool and single spool flow divider

In Fig. 9, the dynamic response of the split spool flow divider spools displacement for different supply flow rate; namely Q_{s1}=0.06 l/s, Q_{s2}=0.08 l/s, Q_{s3}=0.1 l/s, for a load pressure of 40 bar has been plotted. It could be drawn that the increase of the supply flow rates at the same load pressure will increase the split spool flow divider valve spools displacements equally in trend for the both spools at the same given response time.

In Fig. 10, the dynamic response of the split spool flow divider outlet ports flow rates for different supply flow rate; namely Q_{s1}=0.06 l/s, Q_{s2}=0.08 l/s, Q_{s3}=0.1 l/s, for a load pressure of 40 bar has been plotted.

It could be drawn that the supply flow rate is equally divided between the two outlet ports of the split spool flow divider valve where the dynamics of the flow rate time to reach the half of the supply flow rate is increased with the increase of the supply flow rate.

While in Fig. 11, the dynamic response of the split spool flow divider outlet ports flow rates for a supply flow rate of Q_{s2}=0.08 l/s but for different applied load pressure at each outlet port, load pressure at port A is varying from 30 to 50 bars while that at port B is 25 bar.

It could be noticed that the increase of the difference between the two applied load pressures will affect the outlet flow rates from the flow divider valve, at a difference of about 20% the outlet flow rate from the flow divider will not affected while with the increase of the difference applied load pressure will introduce a significant difference between the two outlet flow rates.

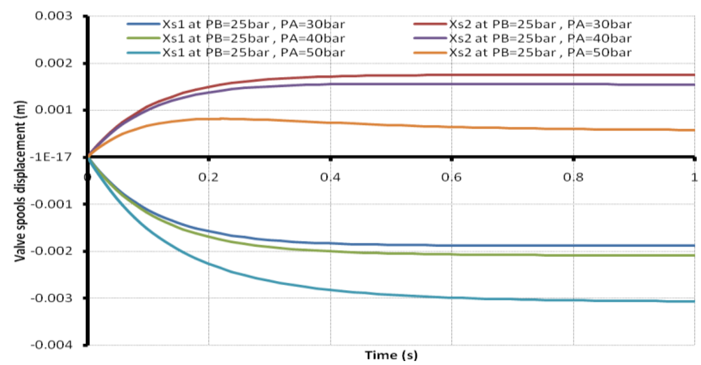


Figure.9. Dynamic response of the flow divider spools displacement for different applied load pressures at flow divider outlet ports A and B.

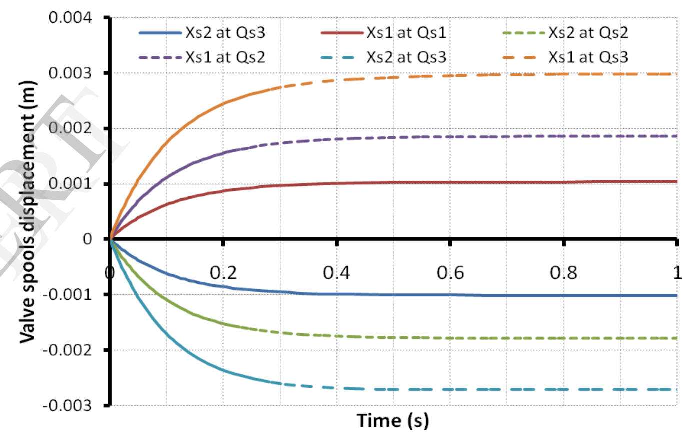


Figure.10. Dynamic response of the flow divider spools displacement for different supply flow rate; Qs1=0.06 l/s, Qs2=0.08 l/s, Qs3=0.1 l/s, for a load pressure of 40 bar.

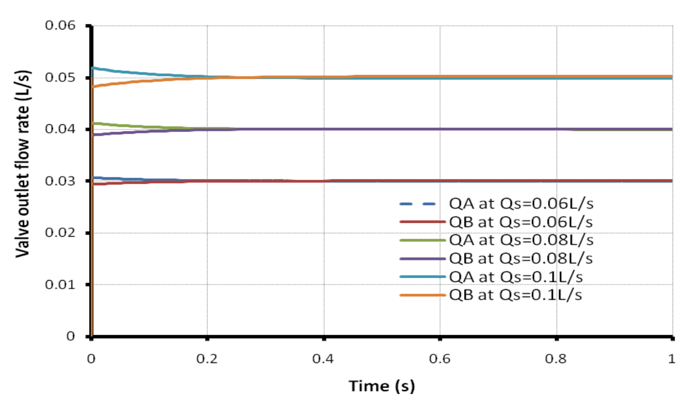


Fig.10. Dynamic response of the flow divider valve outlet ports flow rate for different supply flow rates, at load pressure of 40 bar.

5. Conclusions

Experimental and numerical modelling of the flow divider valve, interconnecting spool, have been introduced to study the effect of the load pressure on the flow divider valve static and dynamic characteristics. A direct comparison of the experimental and modelling results have been made and a good agreement has been noticed.

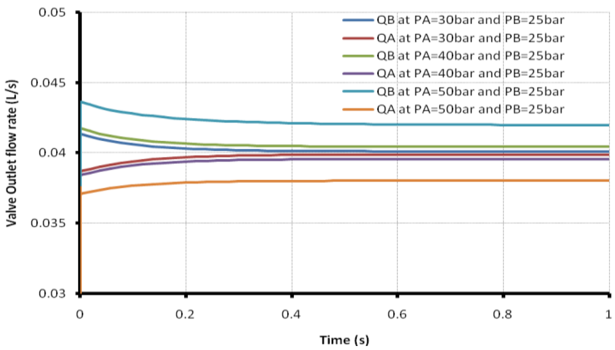


Fig.11. Dynamic response of the split spool flow divider outlet flow rates for different applied load pressures at outlet ports, supply flow rate of 0.08 l/s.

The flow divider of interlocked spools has a significant effect on the dynamics and static characteristics of the flow divider valve in the studied load pressure range up to 50 bars, as this feature decrease the valve inertia due to the lower coupled mass, two split masses instead of one moving spool, and increase the valve response. Consequently, the natural frequency of the flow divider valve has been increased which enhance the flow divider performance due to low overshooting of the dynamic performance of this new features in the special type flow divider valve

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