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DYNAMIC AND STEADY-STATE ANALYSIS OF SPLIT SPOOL FLOW DIVIDER VALVE

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ABSTRACT

Flow divider valve is a critical hydraulic component for which it used to synchronize actuators motion in a predetermined ratio. The flow divider valve types divided into a gear type flow divider and a spool type flow divider valve in which the spool has a rigid connection between the two ports. As a special construction, here, a split type spool flow divider has been studied to investigate the effects of special features on the static and dynamic characteristics of the flow divider valve.

The construction of a special type flow divider valve, split spool type, has a compensating spool/orifice mechanism to maintain equal pressure drops across the valve metering orifice regardless of the change in system load. This split spool flow divider valve thought to have a low inertia effect and enhanced valve response.

In the present work, the static and dynamic characteristics of this special type flow divider valve, split spool valve, have been studied at different load pressures. Experimental test rig has been established to investigate the effect of system pressure on the static characteristic of the special flow divider valve. A mathematical model has been carried out to study static and dynamic characteristics of the flow divider valve; the model has been verified by direct comparisons with the experimental results.

For the dynamic response of the split spool flow divider; with the increase of the supply flow rates at the same load pressure, split spool flow divider valve spools displacements will increase equally in both spools at the same given response time. The supply flow rate is equally divided between the two outlets ports of the split spool flow divider valve will reach the half of the supply flow rate at rate increased with the increase of the supply flow rate.

The comparison between experimental and mathematical model has a good agreement for the studied system pressures up to 50 bars. It has been found that this special type flow divider, split spool type, has a low inertia effect and enhanced valve response at the studied load pressure regimes.

KEY WORDS

Flow divider valve, split spool type, valve modeling, hydraulic valve static and dynamic characteristics.

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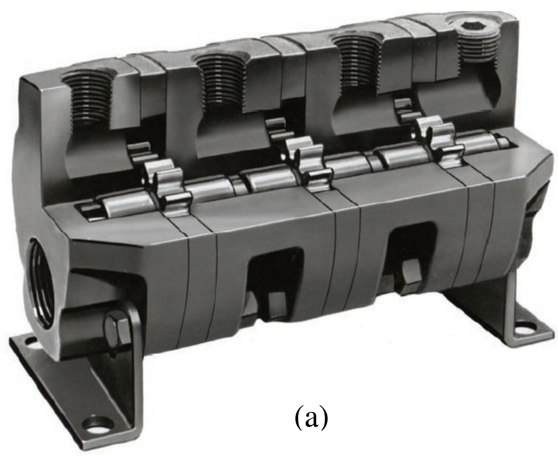
INTRODUCTION

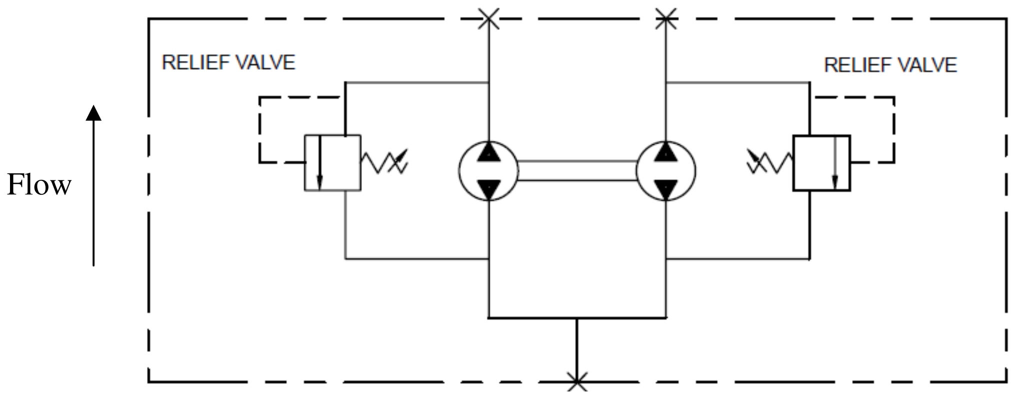
Ideally, flow divider valve splits a single flow source into two or more parts equal or unequal under a specified predetermined ratio regardless of load conditions or system lines pressure. In practical applications, any change in the load pressure will cause force imbalance on the compensating spool, which will alter the flow rates through the metering orifices and affect the control accuracy consequently.

There are two types of flow dividers; rotary flow divider valve, known as gear type flow divider valve as shown in Fig. 1, and sliding spool divider valve, known as spool type flow divider valve as shown in Fig. 2. Each type has its own set of performance characteristics such as flow range, pressure capability, accuracy and the application parameters.

When using spool type flow dividers, several areas of application sensitivity must be taken into consideration such as flows below the designated operating range, entrapped air, and/or contamination which can cause these devices to produce inaccuracies larger than the individual cartridge-specified tolerance limits.



(a)



(b)

Fig.1. Rotary type flow divider valve; (a) detailed construction, (b) hydraulic circuit.

As the flow dividers should accurately divide the flow from a single hydraulic source into two or more equal or proportionate circuits, the input pressure required will be proportional to levels of flow/pressure out of the flow divider. Hence, improving the flow divider valve accuracy will depend on how the division element works here the special type spool element, has affected the static and dynamic characteristics of the flow divider valve.

Over the past years, industrial manufacturing companies have tried to successfully design flow divider valves to divide and/or combine flows with a minimum error and high response independent of the system loading conditions. Recently, these companies manufactured a special design flow divider valve with split spool for a wide range of flow applications; this special valve is the valve under investigation in the present work.

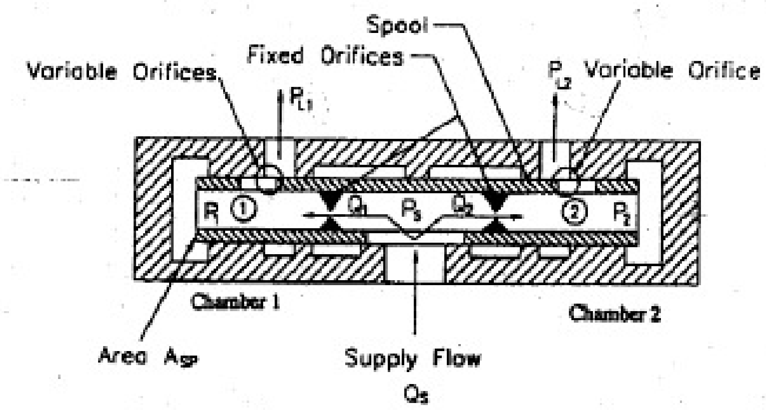


Fig.2. Spool type flow divider valve main construction.

Fedoroff et. al. [1] investigated the characteristics of flow divider valve with a linearized model developed based on number of valve parameters. In addition, model based on Power Bond Graph technique is presented and the transient responses to different flow inputs have been compared with experimental results. The model and experimental responses were in good agreement. Based on that result, they suggested that the established model could be used in future stability studies.

Cheng [2] studied the static and dynamic characteristics of a flow divider valve numerically by solving the characteristic equations. It has been shown that flow force is the main factor to affect the flow division accuracy. The flow division error increases with increasing the load differential pressure, centering spring constant, and metering orifice area, also the centering spring constant has no obvious effect on the valve dynamic response.

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 Figs. 3 and 4, is of special type which dividing the flow from a single hydraulic source into two equal flow rates to synchronize the system actuators.

Figure 3 showed the schematic drawing and the model of split spool flow divider. In this construction, the special type flow divider has a split spool in which the two chambers, chamber 1 and chamber 2, spools are split to reduce the inertia of the

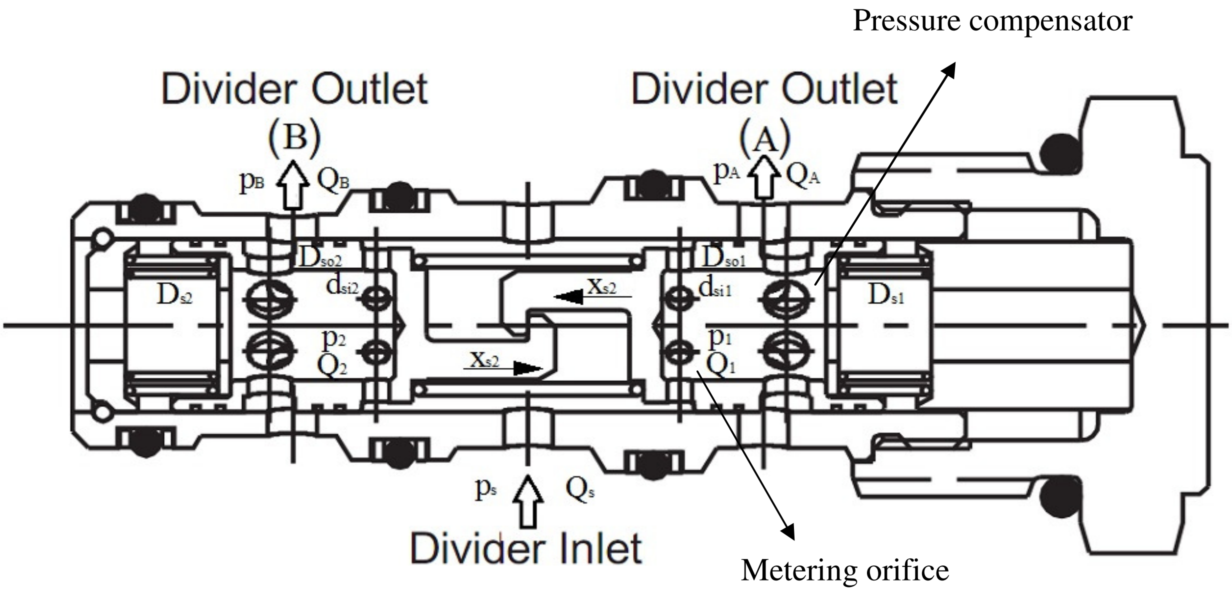


Fig.3. Split spool flow divider valve internal construction.

moving parts and to ease the controllability of the flow divider valve to the different load pressures. The split spool flow divider has the advantage of separately control the two loads with split spool which enhance the performance and give easy adaptation to the flow ratio change and the maintenance. This new feature introduced the effect of the two flow regulator combined together.

While in Fig. 4, the hydraulic circuit of this special type flow divider valve is illustrated; when fluid flows into the valve with flow rate Q_s, it is divided through the two fixed orifices into chamber 1 and chamber 2 with the equal area of outlet orifices, if equal division of flow rate is desired for different load pressure, the pressure drops, $p_s - p_1$ and $p_s - p_2$ must be equal.

With different load pressures due to unequal load, p_1 and p_2, the split sliding spools have been moved to compensate the pressure variations through controlling the outlet ports orifice areas which increase or decrease the pressure drop across these orifices until the flow rates from the valve ports are equal.

The split sliding spool works to open/close a variable throttling orifice inside the valve between the flow chamber (1) to the flow divider output port (1) and close/open a variable throttling orifice inside the valve located from chamber (2) to flow divider output port (2).

Herein, an experimental and theoretical investigation of a special flow divider valve, split spool type, have been carried out. The modelling of flow divider valve equations is introduced and SIMULINK is used to investigate the static and dynamic characteristics of this special valve. The objective in this study is to study the valve behaviour for different load pressures. Experimental setup is established to validate the static results of the split spool valve from the mathematical model.

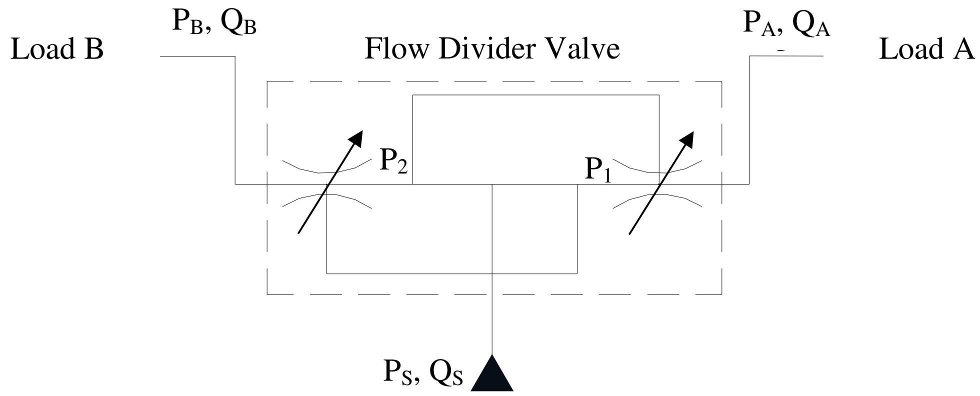


Fig.4. Split spool flow divider circuit.

This paper is organized as follows; in section two, the experimental set up has been illustrated. In section three, modelling and simulation of the hydraulic circuit are introduced while the results and discussions are presented in section four and the conclusion will be addressed in section five.

EXPERIMENTAL STUDY

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. 5.

The hydraulic circuit under investigation, as shown in Fig. 5, consists of a power pack (1); a hydraulic reservoir, a gear pump with a relief valve, connected to the hydraulic bench (2). The component under investigation is the flow divider (5) connected to the pressure transducers in the inlet port and the outlet ports, and flexible connections have been inserted between the flow divider valve and the system outlet lines pressure to eliminate the effect of the load dynamics on the flow divider characteristics.

The main measured parameters of the hydraulic circuit are the input pressure, flow rates 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.

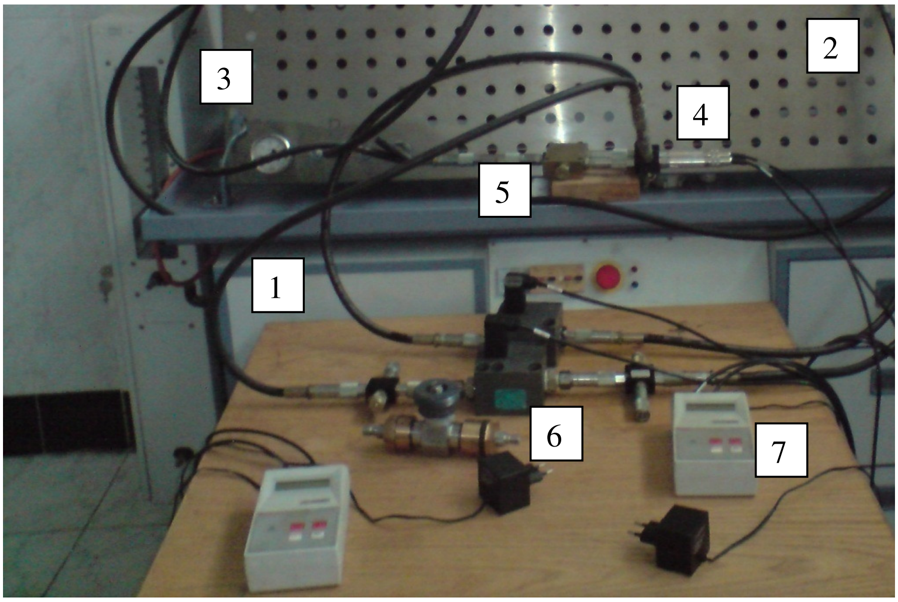


Fig.5. Experimental set up; (1) power pack unit, (2) hydraulic bench, (3) inlet control valve, (4) pressure transducer, (5) flow divider, (6) digital flow metre, (7) flow meter readout.

MODELING AND SIMULATION OF THE HYDRAULIC CIRCUIT

The circuit diagram of the investigated hydraulic circuit is shown in Fig. 4. The special type flow divider, split spool valve, has been studied in order to obtain its mathematical model. Then, the flow divider valve is modelled using SIMULINK program to find out its static and dynamic characteristics [3-8]. The split spool flow divider under investigation has been described by system of equations as the following:

The Flow Rate Equations for Flow Divider Spool

The flow rate through the flow divider orifices, Q_1 and Q_2, could be related to the supply flow rate as follows, the Pump delivers constant flow rate with oil density, viscosity and bulk modulus of constant value and the return line pressure is the atmospheric pressure:

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

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

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

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 assumed to be constant of 850 kg/m^3.

The flow rate equations at flow divider outlet:

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

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

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

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

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.

Split 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. 7:

$$(p_1 - p_s)A_{s1} = -m_{s1}\ddot{x}_{s1} + C_3\dot{x}_{s2} - (C_1 + C_3)\,\dot{x}_{s1} + k_3\,x_{s2} - (k_1 + k_3)x_{s1} \tag{10}$$

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

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

The calculation of the flow variables such as p_s, Q_A, Q_B, p_1, p_2, p_A and p_B are figured out from Equations 1 to 11. The known values are the input flow to the flow divider valve, Q_s, and the outlet load pressures, p_A and p_B. The orifice geometrical constants are all taken to be fixed.

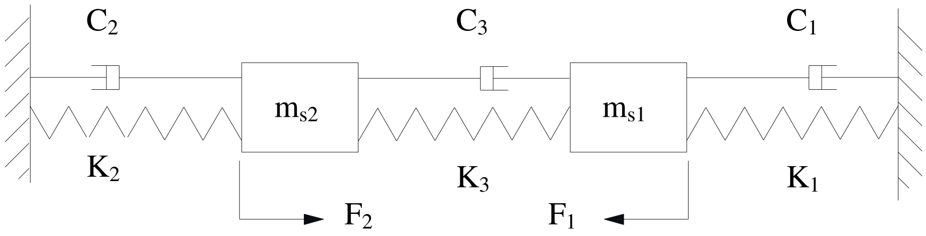


Fig.6. Equevilant flow divider mass spring dumper system.

RESULTS AND DISCUSSIONS

The results for the split spool 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 Split Spool Flow Divider Valve

The static characteristics of the flow divider have been plotted for experiment and simulation results. In Fig. 7, a direct comparison has been made between the experimental results and the simulation results for the load pressure variation of the flow divider up to 50 bars. 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 bars.

In Fig. 8, 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. This may highlight that this split spool valve should be applied in loads larger than 15 bars, it has low sensitivity at low pressure, and the dominant working range for this split spool valve is around 30 to 50 bars where the error is reduced.

As it has been noticed from the literature survey, the error of the investigated flow divider in [1] by using autoregulator valve connected to the flow divider has order of 3% with this modification. In the current study, the maximum error in the flow rate for this special flow divider valve, split spool valve, was of order 4% without any external addition to the flow divider valve. This results means that this split flow divider valve does not need any regulator to achieve the accurate division of the flow because it has its own regulator built in.

Dynamic Characteristics of Split Spool Flow Divider Valve

The dynamic characteristics of split spool flow divider spools displacements and outlet flow rates as function of the load pressure have been plotted in Fig. 9 to 12. In Fig. 9, the dynamic response of the split spool flow divider spools displacement for

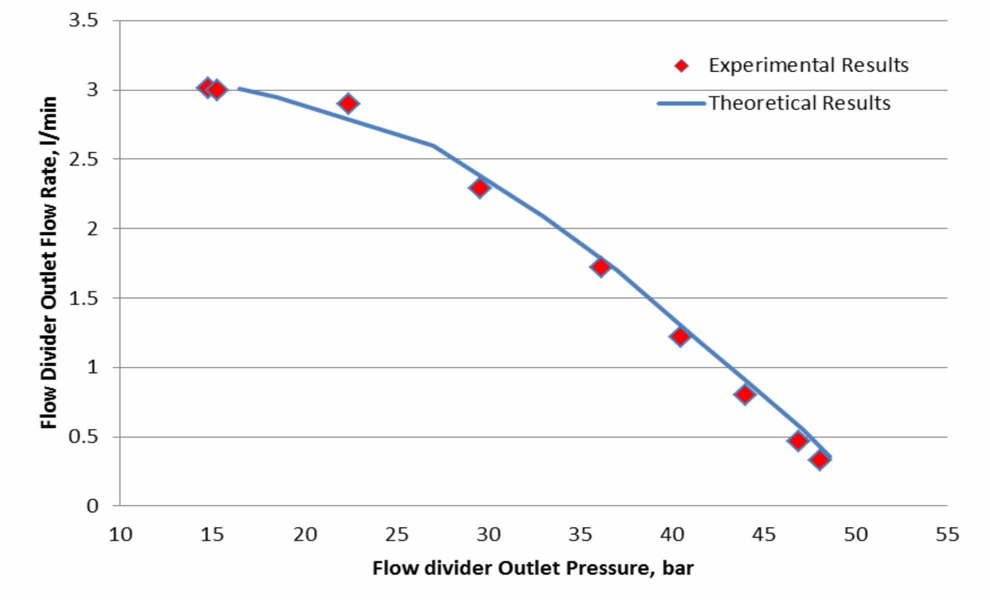


Fig.7. Experimental and theoretical results for the split spool flow divider outlet the outlet flow rate as function of the outlet pressure; same load pressure applied at each port.

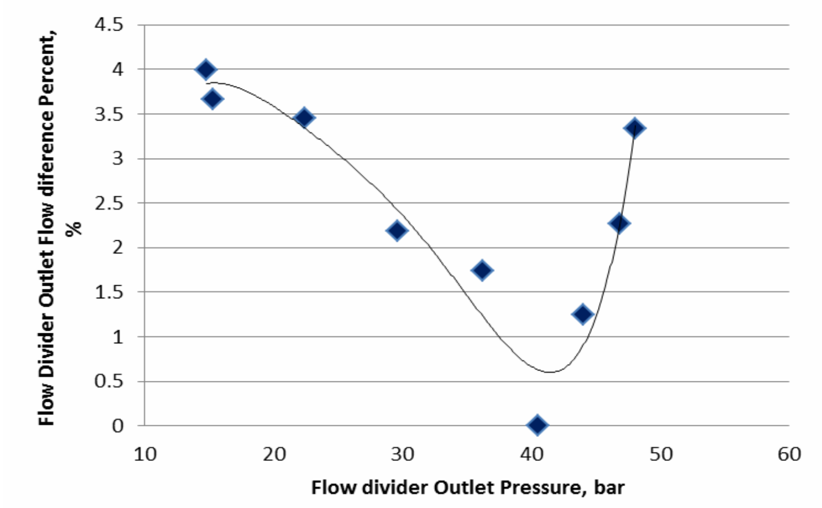


Fig.8. Difference between the outflows of the split spool flow divider ports in %.

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 at the two outlets ports 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 responses of the two spools displacements, spool 1 and spool 2, for different load pressures have been plotted. 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.

In Fig. 11, 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. 12, 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.

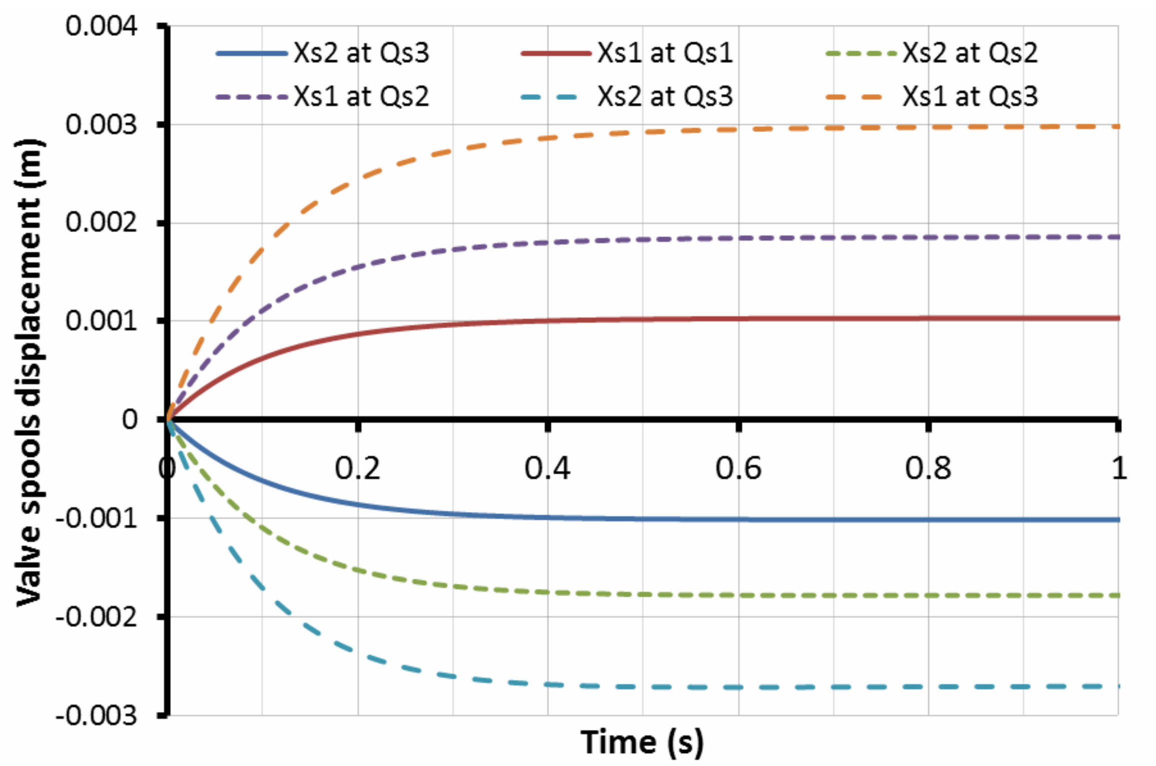


Fig.9. Dynamic response of the split spool flow divider spools displacement for different supply flow rate; Q_{s1}=0.06 l/s, Q_{s2}=0.08 l/s, Q_{s3}=0.1 l/s, for a load pressure of 40 bar at the two outlets ports.

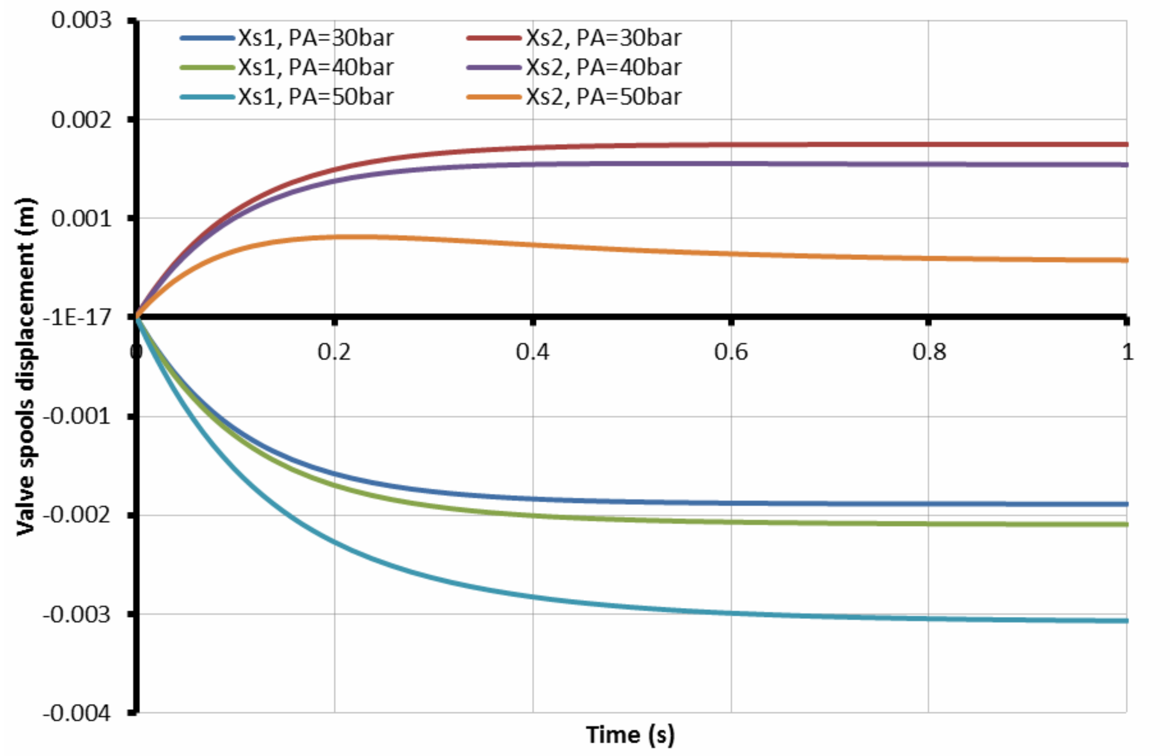


Fig.10. Dynamic response of the split spool flow divider spools displacement for outlet port B pressure of 25 bar and different applied load pressures to port A.

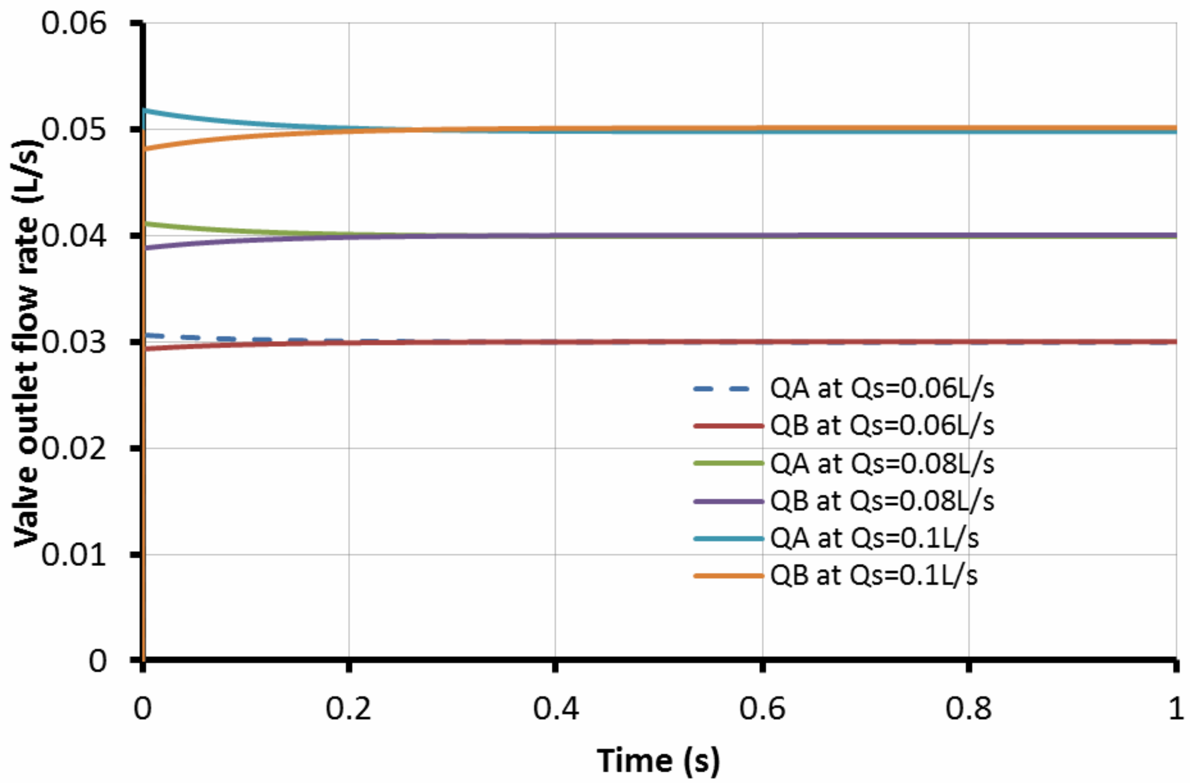


Fig.11. Dynamic response of the split spool flow divider valve outlet ports flow rate for different supply flow rates, at load pressure of 40 bar.

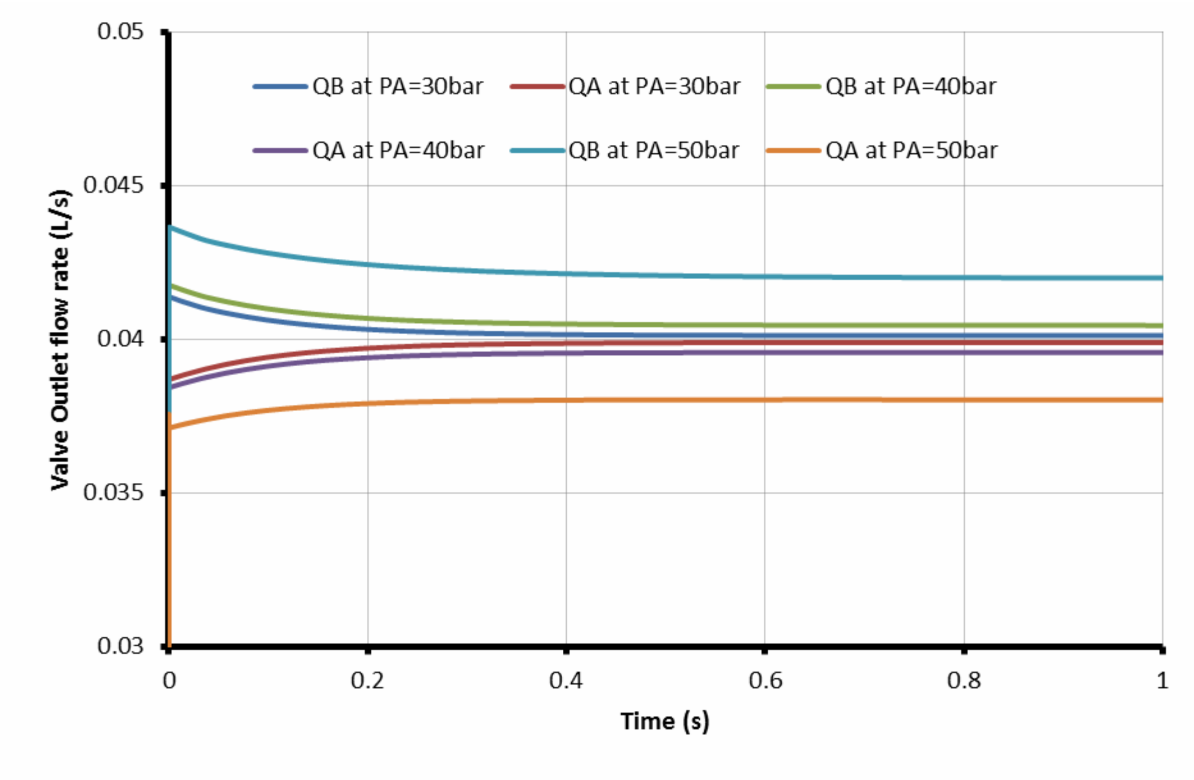


Fig.12. Dynamic response of the split spool flow divider outlet flow rates for outlet pressure at port B of 25 bar and different applied load pressures to port A, supply flow rate of 0.08 l/s.

The special type flow divider of split spool 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.

CONCLUSIONS

Experimental and numerical modelling of special type the flow divider valve, split spool, have been introduced to study the effect of the load pressure on the flow divider valve static and dynamic characteristics. Different applied load pressure and supply flow rate have been introduced to investigate their effect on the static and dynamic response of this special type flow divider valve.

For the dynamic response of the split spool flow divider; with the increase of the supply flow rates at the same load pressure, split spool flow divider valve spools displacements will increase equally in both spools at the same given response time while the supply flow rate is equally divided between the two outlet ports of the split spool flow divider valve will reach the half of the supply flow rate at rate increased with the increase of the supply flow rate.

Also, with the increase of the difference between the two applied load pressures 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.

In addition, in the current study, the maximum error in the flow rate for this special flow divider valve, split spool valve, was achieved of 4% without any external additional component to flow divider valve. This results means that this split flow divider valve does not need any regulator to achieve the accurate division of the flow because it has its own regulator built in with the independency of the controllability of the two split spools which enhance the flow adaptation and the maintenance.

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