Simulation of proportional control of hydraulic actuator using digital hydraulic valves

IOP Conf. Series: Materials Science and Engineering **263** (2017) 062080 doi:10.1088/1757-899X/263/6/062080

Simulation of proportional control of hydraulic actuator using digital hydraulic valves

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Abstract. Fluid power systems using oil hydraulics in earth moving and construction equipment have been using proportional and servo control valves for a long time to achieve precise and accurate position control backed by system performance. Such valves are having feedback control in them and exhibit good response, sensitivity and fine control of the actuators. Servo valves and proportional valves are possessing less hysteresis when compared to on-off type valves, but when the servo valve spools get stuck in one position, a high frequency called as jitter is employed to bring the spool back, whereas in on-off type valves it requires lesser technology to retract the spool. Hence on-off type valves are used in a technology known as digital valve technology , which caters to precise control on slow moving loads with fast switching times and with good flow and pressure control mimicking the performance of an equivalent "proportional valve" or "servo valve".

1. Introduction

Fluid Power systems have been in existence for many decades. They have been classified as Pneumatics (low cost) and Oil Hydraulic systems (medium and high costs).Technology has advanced to such a great extent that present day requirements need high pressures and high loads but at the same time comparatively lower costs. So the term digital hydraulics has come into existence. Electronics has provided a lot of advantages like sensing, control and accuracy of hydraulic systems. But the costs involved in large scale or even medium scale hydraulics is prohibitive due to the costs of the electronically advanced valves like servo valves, proportional valves .Also another problem with servo valves is that if stuck in one position a very high frequency is needed to bring the valve spool to normal position.

So therefore in the past decade or more technology has been developed to make hydraulics low cost but digital to get better position control and accuracy. The concept of digital hydraulic valves started with the requirements of minimizing energy losses, costs and improvement in tracking or control performance. The idea of making digital hydraulic valve technology was to have on/off valves in combinations of 2s to have a binary combination or code to achieve much better proportional or ramp control using on/off valves. On/off valves on their own give step inputs individually giving either full flow or no flow. But in a combination with many similar on/off type valves in ratios of 2s give a proportional flow output much better than the proportional or servo valves. This is seen from the work of [5] where he has simulated the idea of using valves as a mechatronics package with binary code for position tracking of cylinders.

The authors in their paper [7] have used parallel-connected two-way on/off valves together with intelligent controls used to implement the digital hydraulic control of the cylinder and concluded that the above method is energy efficient. Another researcher [3] in his work on high flow on-off type of

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valves uses 4×2 on/off valve as a 2× 2 valve for high flow control proving that digital hydraulics enables high flow without throttling.

Yet other authors in their work [1] on fast switching valve for digital hydraulic systems, have demonstrated how switching valves can be used as pulse-width modulation. Also the valve is so constructed that it has low flow i.e. 65l/min at 10bar, minimum leakage and a flow gain. Their systems works in such a way to actuate the valve to switch flow between high and low pressure supply ports within a millisecond with a square wave response. Another group of researchers [2] have ventured on a distributed valve system which enables several modes of control . Such control modes are necessary for reducing the energy consumption. In other words the traditional hydraulic cylinder having a limited number of control modes, with a multi-chamber cylinder, the control modes are liable to increase.

The researcher [4] in his work on theoretical and experimental studies of a switched inertance device have designed it for flow control and pressure in a hydraulic supply. This device consists of a switching element, an inductance and a capacitance which is necessary to increase the pressure or flow with a corresponding drop in flow or pressure, In their paper, in the frequency domain, the effect of switching, non-linearity and leakage of the valve, is considered and verified by simulating and experiments. The authors [6] in their article on digital valve control have mimicked a 3-way directional valve as four 2-way on/off valves. Five different digital control methods have been discussed and studied. The aim of their study was to find the best digital control method for a DC on/off valve combination.

The work [7] in their paper on Digital Hydraulics used parallel-connected two-way on/off valves together with intelligent control in order to study the energy efficiency of a high inertia cylinder drive system.. A manifold block housing 4×5 two-way screw-in cartridge valves is used for digital hydraulic control of the cylinder. A cost function is used for minimization of power losses. Different loading conditions and switching logic between different flow modes is investigated.

Researchers [8] in their work on a position tracking control system made use of a pulse code modulation method to get step flow control for a series of four valves, each containing two-way solenoid valves four in number. The authors observed that good control was possible at low speeds with hree or four valve series being open together. Other authors [9] in their paper on valves have traced the history of miniature valves and how they can be made smaller and used in digital hydraulic control in a more efficient since normal on/off valves are bulky and need lot of space for plumbing.

The researcher [10] in their paper on digital fluid power systems have analyzed the components with for dynamic performance, controllability and reliability. They have concluded that for on/off type valves for application in digital displacement motors and pumps, the permitted valve switching times are not proportional to the revolution speed. Hence they have developed a working model of a single -stage, quick switching on-off type of valve. The authors [11] developed an on/off valve based trajectory tracking control solution with slow and intermittent switching of valves. They have used pulse code modulation method to obtain stepwise control of flow in and out of the actuator. The obtained result is similar to that of a water based servo valve control action.

Researchers [12] in their work on digital hydraulics related to aerospace applications have demonstrated that such systems are energy efficient. Also the author [13] in his work on digital hydraulics has achieved switching of the on-off type valves at almost zero flow rate.

The objective of our work is to compare the performance of the single cylinder with load when controlled with a set of 4 bit on-off valves replacing proportional and control valves. So the parameters for which the performance is considered is pressure, speed, position and binary code (analogous to flow performance).Binary codes developed are used as input controls for monitoring the performance of the actuator. Finally the main aim of the work is to ensure a simulation of binary coding control for the actuator and monitor the performance. So it is observed that even if one of the on-off valves fails, the performance does not affect the actuator.

2. Modelling

The circuit diagram of a combination of a 4 bit binary code valve setup has been developed in Automation Studio and with the aid of a PLC program; the actuation of the valves for both forward and return stroke of the cylinder has been undertaken. The set of valves obey the binary code of 1:2:4:8, the corresponding ratios of flow. In other words a series of on/off valves are arranged for extension, retraction and return flows in the form of a 4 bit binary code .Finally the various plots indicate not only the ramp outputs both in extension and retraction, but also the piston and rod side pressures during forward and return stroke of the actuator. Increasing the number of valves for higher order binary results in better servo or proportional like control for one or a set of actuators.

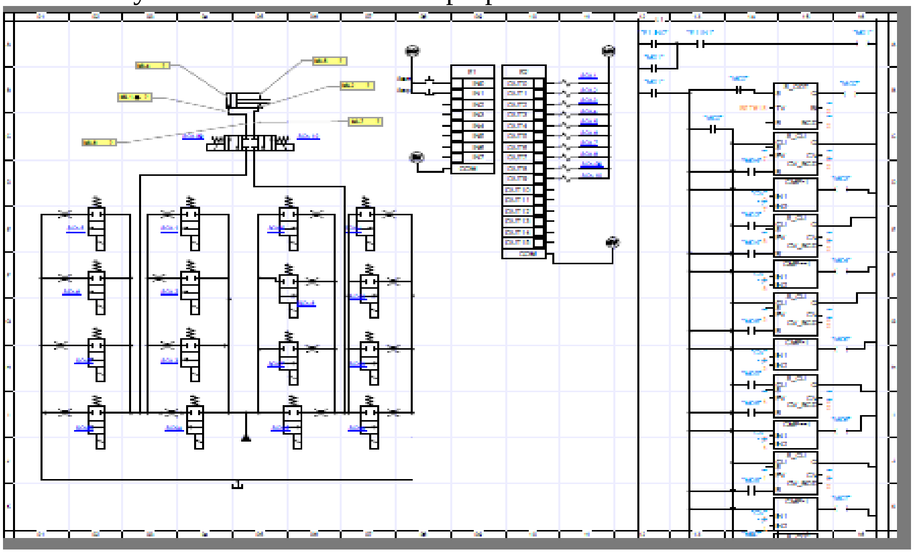

Figure 1. Four bit DFC Hydraulic circuit with PLC program

Figure 1 shows the simulation of the entire model of the hydraulic circuit and part of the PLC program and control pulse for solenoid valve set in our work.

Calculations of the flow through the valve orifice are indicated below:

$$Q=0.0851*C*A*\sqrt{(\Delta P/SG)} \quad (1)$$

Q = flow rate (l/min).
C = flow co-efficient (C = 0.8 for sharp edged orifice, 0.6 for square edged orifice)
A = area of the orifice opening (mm^2) = $A=(\pi d^2)/4$
d = diameter of the orifice (mm)
ΔP = P1-P2 = pressure drop across orifice (kPa)
SG = specific gravity of flowing fluid.

Sample calculation for orifice flow:
For Q = 0.4 l/min, ΔP= 500 kPa , C = 0.8, SG = 1,
Upon substitution in the equation (1) we get d = 0.5784 mm.
Likewise,
For Q = 0.8 l/min, d = 0.8179 mm.
For Q = 1.6 l/min, d = 1.1568 mm.
For Q = 3.2 l/min, d = 1.6359 mm.

The model has been developed in Automation Studio and the electrical control of the solenoids is obtained by means of a ladder logic PLC program. The circuit diagram is akin to a 4 bit binary code with the lower part of the circuit corresponding to the LSB and the top part of the valve circuit is the MSB. So the ratio of the flows emanating from the DC valves is 1:2:4:8 from bottom to top (LSB to MSB).The valves are arranged in parallel to get the maximum benefit of the summed flows of individual valves both in extension and retraction. One set of valves are used for extension (second column from the left) and one set of valves are used for retraction (third column from the left) in the circuit diagram. The right and left extremes of the valve columns represent the return flows to the tank during extension and retraction. The PLC indicates the operation in the form of a truth table of 0s and 1s to indicate which valve or valves are in operation in a binary code 4 bit sequence, represented by the 4 sets of valves.

3. Simulation Results

The plots have been shown with time on the x axis, with position, speed, piston side, pressure, rod side pressure plotted on the y axes respectively. Other plots indicative of valve outputs represent the LVDT like behavior of the solenoid valves position with respect to time. The performance of the actuators and the valves is comparable with the works of other researchers except that some researchers have used a 5 bit set of on/off valves which cannot be classified as a binary arrangement of powers of 2.The results compare well with the research work of others indicating the periodic piston pressure and the rod side pressure behavior with respect to time.

The velocity time graph indicates the cyclic ramp like pattern of the graph indicating repeated performance and compares with the cyclic operation of actuators researched by other authors in their work. The position time response of the cylinder indicates a sinusoidal type of output indicating the response of the valve matching the performance plots of other researchers .The valve response time is set for 100 milliseconds which can be varied depending on the requirement, of speed of response.

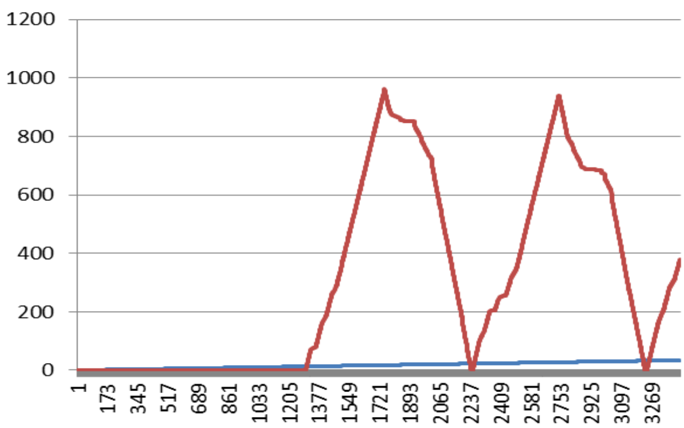

Figure 2. Position Vs time

Figure 2 shows the actuator position with respect to time with a time delay of 100ms. The plot indicates that there is a rise in pressure during acceleration and a decrease in pressure during deceleration hence the position graph looks like the above. The graph shown below also indicates the same nature of the curve except that there is an increased time delay of 1 sec. This means that by varying the time delay the pressure changes during acceleration and deceleration phase of the actuator resulting in control of the actuator. But the inertias are small of the valves; hence we can expect sharp changes in the nature of the graph.

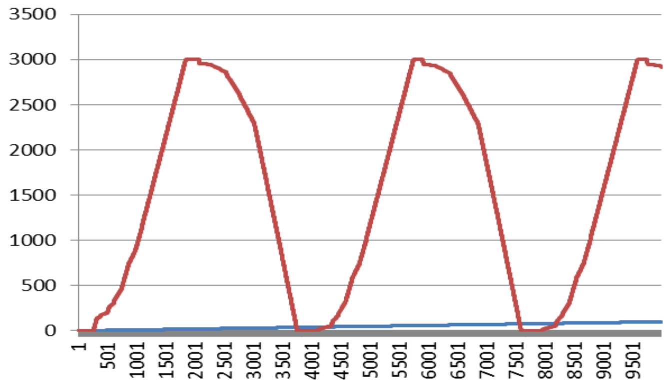

Figure 3. Position Vs time

Figure 3 indicates the position of the actuator with respect to time with a time delay of 1 sec. This means that with a larger time delay, the valves switching times are also slower which means smoother curves and variation in pressure.

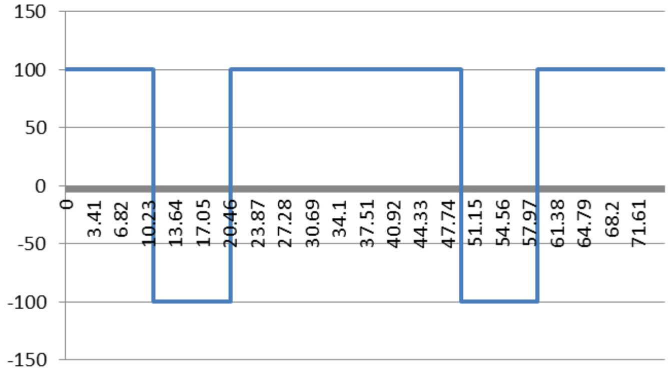

Figure 4. Control Pulse for solenoid valve 1

Finally the above graph in Figure 4 indicates the position or displacement of the spool of the solenoid valve 1 with time. The valves opening and closing (switching) is shown in the above graph with a maximum opening of +/- 100 mm for a maximum time period of 71.61 sec. This indicates the displacement of the solenoid operated valve with respect to time.

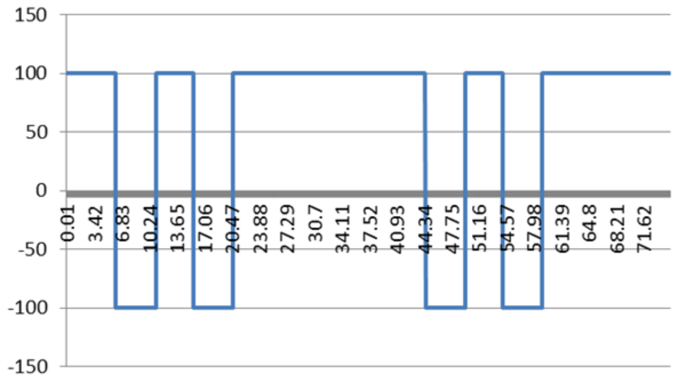

Figure 5. Control Pulse for solenoid valve 2

The above graph in Figure 5 indicates the position or displacement of the spool of the solenoid valve 2 with time. The behavior of the valve spool is similar to that except that it may open after valve 1 depending on the sequence of operation in the truth table.

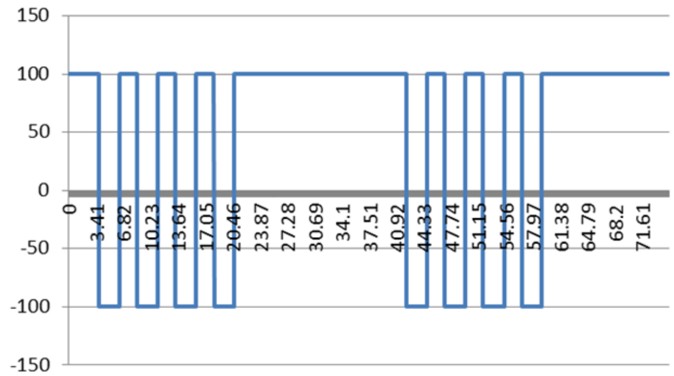

Figure 6. Control Pulse for solenoid valve 3

The above graph in Figure 6 indicates the position or displacement of the spool of the solenoid valve 3 with time. Likewise from the above graph it is seen that valve 3 opens but as a different response and faster ,in order to have faster flows in combination from LSB to MSB. The valve opening is also based on the inertia of the spool.

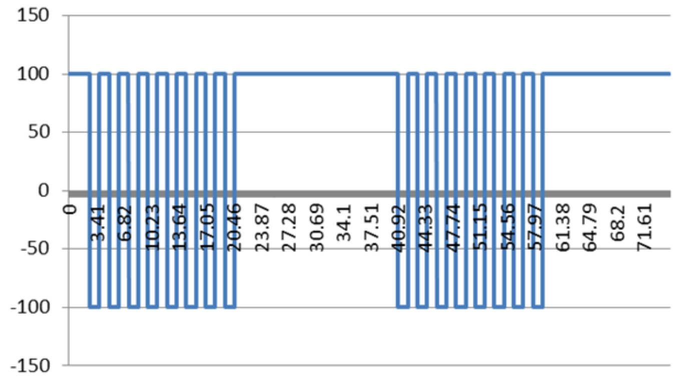

Figure 7. Control Pulse for solenoid valve 4

The above graph in Figure 7 indicates the position or displacement of the spool of the solenoid valve 4 with time. Finally the response of the valve is based on the inertia of the solenoid valves subjected to an electrical input. But the inertias are not high and small to permit fast switching times.

Finally position of valve 4 indicates much faster opening, likewise if there had been 16 valves etc. then the farther valves would have opened much faster indicating faster switching times and larger combinations of flows based on the binary codes and hence better control.

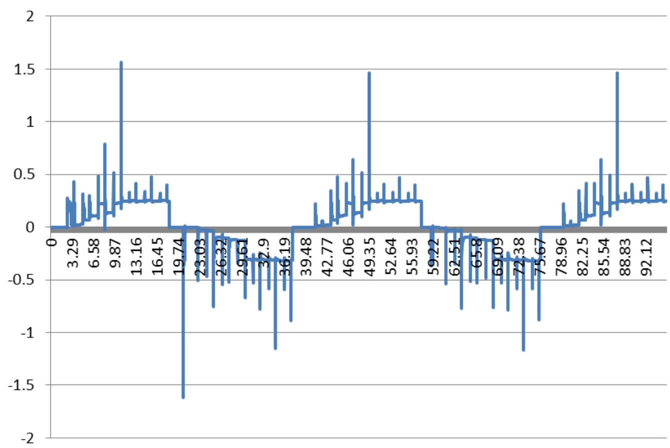

Figure 8. Velocity Vs time

The plot of Figure 8 shows the velocity with respect to time of the actuator. The above graph indicates the variation of velocity up to a maximum of 2 m/sec both in extension and retraction strokes with respect to a time of 95.0 sec. This means that the velocity tracking will be smoother if more number of valves are used but if less number of valves are used the tracking is not smooth and hence causes jerky movements of the actuator.

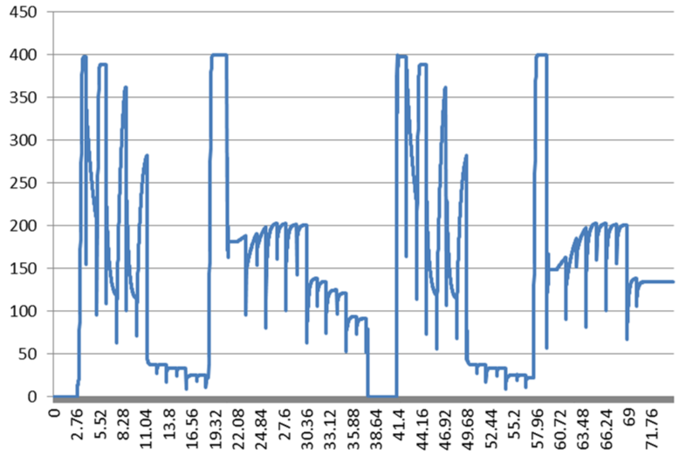

Figure 9. Pressure(MPa) at port A(piston side) Vs time

The above plot in Figure 9 indicates the pressure variation of the piston of the cylinder with time. It is seen that with each cycle the piston pressure peaks to a pressure of 400 bar for a time period of about 80 secs. The pressure behavior might be due to the fact that we are using switching valves, output not being exactly analogous results in variation.

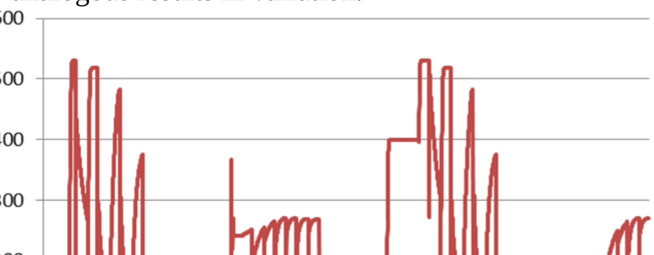

Figure 10. Pressure (MPa) at port B(rod side) Vs time

The above graph of Figure 10 illustrates the variation of cylinder rod side pressure with time The above graph shows the variation of rod side pressure with time .Since the rod is slimmer than the cylinder ,the pressures on the rod side may be higher.

4. Conclusion

The velocity time graph is a cyclic ramp indicating slow acceleration and faster deceleration before halting of the actuator. The position time response of the cylinder indicates a sinusoidal type output which shows a cyclic rise and fall of position with respect to time. .The valve response time is set for 100 milliseconds as well as 1 sec which can be varied depending on the requirement of speed of response required for the particular actuator. The plots of the piston side and rod side actuator pressure

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indicate the scenario for design of the piston and rod assembly. The precision and accuracy of such systems are dependent on the valve switching times based on the actuator extension and retraction requirements. This ranges from 100 milliseconds to 1 sec response time of the valve as already mentioned earlier.

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