Digital hydraulic valves - a brief review

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ABSTRACT

Digital Hydraulics is a recently developed substitute for conventional control with servo or proportional valves in hydraulic control systems. Digital hydraulic systems have been developed during the last decade. Digital hydraulic systems are used in applications like configurable, outer-loop motion and pressure closed-loop controls. Digital hydraulic valves in these systems can provide open architecture. High performance control with good energy efficiency has been observed with these valve systems. The advantage of such systems is that we can use on/off valves in place of servo or proportional valves where motion and control problems are critical. This paper reviews the characteristics, modelling and control optimization of digital hydraulic valves. A small number of researches were made on design, development, simulation and modelling of digital hydraulic valves for high performance and energy savings, especially for low velocity systems with precision and accuracy. Many researchers have been reported energy efficient, better position and velocity control with digital valves.

KEY WORDS: Digital valve, modelling, outer loop, pressure, hydraulic, closed loop, energy efficient.

1. INTRODUCTION

Machines that need high repeatability to ensure high product consistency and low scrap rate, place hefty demands on hydraulic systems. Good reliability is a reason why hydraulics is used in these applications. Precise pressure and flow control ensure high quality and consistent operations. Digital Hydraulics is a recently developed substitute for conventional control with servo or proportional valves in a hydraulic control system.

The digital valves allow hydraulic fluid flow to move machine elements into correct position, and then control pressure applied for precise control for the particular process. The digital valves simplify the system architecture by integrating the functions conventionally performed by proportional or servo valves in a bank of on/off valves. Simple on/off valves are revolutionising the world of hydraulics. Smart digital systems based on these valves offer significantly improved response times and reliability compared to conventional load-sensing technology, as well as major energy savings, according to Ehsan (2000).

The novelty in applying digital principles to hydraulics is by using on/off valves controlled through software rather than using proportional or servo valves. As a result of this pioneering works, on/off type of valves connected in parallel could replace the conventional servo and proportional valves. An example of a product displaying the above principles is a loader developed at IHA working on digital hydraulics. The advantages of such valves are that they are energy efficient with fuel saving of 20-40%.They have other benefits like speed, durability and capability of working in dirty environments when compared to conventional hydraulics. Maintenance and breakdown is minimal because of having large number of valves in parallel. In spite of increasing computing power due to increase in the number of valves, such systems were relevant for improvements in performance, savings in energy and cost cuts by using cheaper valves. This could result in reduction of losses by almost 70%.

The concept involved in digital valve technology is that not only on/off valves are used but they are miniaturised and of the same size according to Palonitty (2015). The authors of this work have developed a small size valve having an orifice or an internal flow passage of diameter 0.7 mm .Since the valves can be many in number in the digital valve bank, a suitable manifold has been developed by the above researchers to accommodate 16 prototypes of the valves. In order to, achieve a digital coding system based on the number of valves, the authors of this work have evolved a Pulse Number Modulation whose output is proportional to the number of valves. A block diagram of the digital valve hydraulic system is introduced in this paper based on the work done by Linjama (2012). This shows in three stages the evolution of the digital valve system.

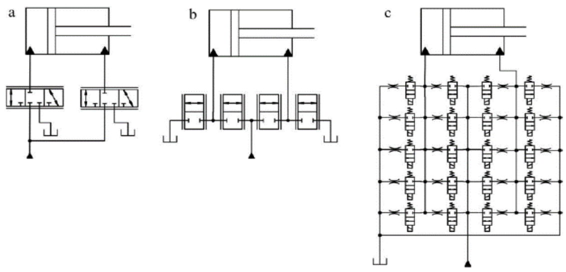

Figure.1 a.2- three way proportional valve distributed system; (b) 4- two way valve system; (c) a digital on-off valve system (Linjama, 2012)

Fig 1-a and Fig 1-b are traditional type of valves (proportional control) normally used for actuation control but not efficient and have to be operated safely. Fig 1-c gives the digital valve solution which is both energy saving and a fast response system.

Karvonen (2014), has endorsed the philosophy of a Digital Hydraulic Power Management System to minimise losses occurring in traditional hydraulic systems. The authors have developed such a system capable of serving many actuators at optimum supply pressure and controlling the inputs to provide suitable output flows with minimum losses. The authors Linjama (2007); Gradl and Schiedl (2014), have developed on/off valves in parallel having good performance and enabling saving of energy. Also in their latter work they have concluded that reducing the sizes of such valves helps in realising equal size valves which result in Digital Flow Control Units. Another significant discovery (Plockinger, 2012), is that the Pulse Width Modulation method of controlling valves uses less number of valves when compared to Pulse Code Modulation. But the authors (Plockinger, 2012) also found that this method though economically viable would generate noise due to fast switching action. The authors have suggested use of notches on the spool body to reduce this disturbance.

Another aspect is the control system considered optimal to operate digital hydraulic systems. The researchers (Gradl and Schiedl, 2014) have studied various control techniques which have been used in digital hydraulic control in the past and as a result of their investigations have suggested the application of a Pulse Frequency Control System for a hydraulic drive in place of a conventional Pulse Width Modulation system. They have modelled the dynamic response behaviour of such systems in order to study the system, since the controlling response for a Pulse Frequency Control system is limited due to the fixed pulse quantity and the maximum repeating frequency.

Though use of on/off valves are normally considered to be digital hydraulics, but researchers (Heikkila and Matti, 2013) have shown that a digital actuator integrated multi-chamber hydraulic cylinder with sixteen piston areas(adjustable piston areas) result in no flow losses, use constant supply pressure and recover the negative power. Also yet other researchers like Heikkila and Matti (2013), have explored the prospects of a Digital Hydraulic Power Management System based on digital pump-motor system with multiple outlets to improve energy efficiency. They have gone beyond digital valve technology in hydraulics.

The authors [(18)] have worked on a hybrid pump system containing poppet valves controlling each cylinder actively. This enables or disables the actuators based on the sequence of strokes. They have modelled the system under varying demand and varying speed for different control actuations. Other researchers (Brown, 1987), in their paper rely on applying switching technology to hydraulic motion. So, in this regard the authors have developed a hydraulic switching converter and compared with a proportional hydraulic valve for an accumulator based circuit for energy consumption.

Digital Valve Characteristics: Other researchers (Palonitty, 2015), have found out that the problem in digital valve control is that at low velocities of the system, precise control is difficult since on/off type valves are used and pulse type signals are given. Their results have shown that Pulse Number Modulation is a better solution for tracking a number of valves at low velocities, one of the methods being increasing the number of valves. The drawback observed in their work is that there is a reduction in position error about low velocities but with oscillations resulting in resonance in the system.

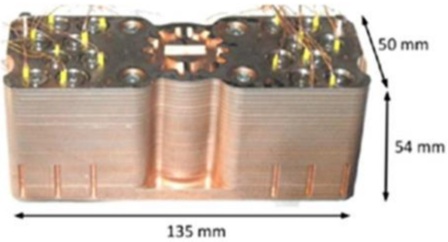

Figure.2. Prototype of digital valves (Palonitty, 2014)

Fig 2 contains the prototype developed by the authors as a prototype with interface (Palonitty, 2015). They have developed a prototype valve for a compact equal coded valve system. The prototype developed by them contains 16 on/off valves. These type of valves arranged together help in developing flows that are controllable and can control actuators with quick changeover, using on/off type of valves, which are connected in parallel. This enables large quantity of flows as well as fast changeover from allowing to disallowing flow into a particular actuator.

In their position tracking system, the authors (Linjama and VIlenius, 2008) using on/off valves in parallel have achieved stepwise flow control with a four valve series with a pulse code modulation approach. They have demonstrated that controllability can be improved at low velocities by permitting three or four valve series to be open at the same time rather than flowing from inlet to outlet and back a number of times.

In the latest developments in digital valve control technology, other researchers (Gradl and Scheid, 2014), have shown that in place of Pulse Width Modulation technique (which uses the width of the pulse as control) they have applied Pulse Frequency Control (pulse repeating frequency) as an input to the hydraulic drive.

The work done in Linjama (2012), expresses the fact that the behaviour of on/off valves is known as either completely open or completely closed, hence there can be no "fuzziness" about the nature of output from such valves. Also the changeover from open to closed or closed position is quick. This type of control approach is used for controlling hydraulic actuators with valve systems connected in parallel. If the valves individual characteristics are predictable then control of such valves becomes easier because the flow capacities are calibrated in exponential numbers of two.

These type of valves arranged together help in developing flows that are controllable and can control actuators with quick changeover, using on/off type of valves, which are connected in parallel. This enables large quantity of flows as well as fast changeover from allowing to disallowing flow into a particular actuator.

The authors emphasized (Linjama, 2009), on the fact that digital hydraulics results in digital valve technology that is capable of both large flows and quick switching rates. The control strategy was well discussed for a digital valve. The authors in their research work have indicated that it is practically feasible to switch a large flow rate digital hydraulic valve at 100 Hz. So in order to prove the concept in sequential steps, the authors have created a valve model with PID controller tuned to stabilize the valve empirically and compared the simulated and measured results. The valve model proposed is indicated below in the form of a block diagram. A sample graph is shown in Fig.2 (Linjama, 2009).

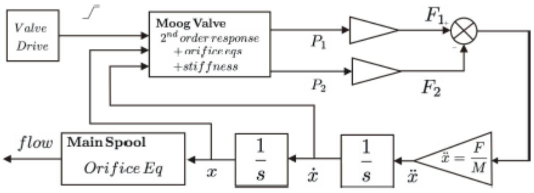

Figure.3. Model of the digital valve spool (Linjama, 2009)

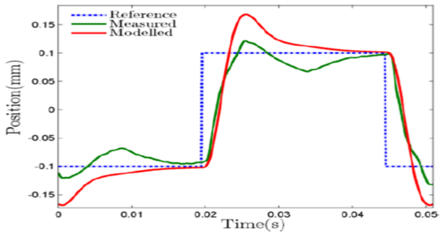

Figure.4. Deviation between modelled and measured output of PID control (Linjama, 2009)

Fig.3 indicates the deviation between modelled and measured output of the system at a frequency of 20 Hz with PID control (Linjama, 2009).

The researches on the characteristics of on/off valves indicate that at low velocities using, pulsed signals precise control is possible. Also they have suggested that at low velocities by combining valves in series better control is obtained. Another significant contribution by some researchers was that knowing the characteristics of such on/off type of valves better control of the valves is obtained by sudden change in position from on to off or vice versa.

The authors (Cui, 1991), in their research paper on digital fluid power systems have established the fact that in digital hydraulic systems, the valve switching timings are inversely varying as the revolving speeds of the digital motor-pump systems. They have developed a working model of the above with switching times of 3 ms for closing and 4.5 ms for actuating of the on/off valves. The time of 4.5 ms is the input providing the operating forces for the load movement.

Digital valve modelling: The researchers (Linjama, 2012), in their paper developed a flow model which represents the flow characteristics of different valve-orifice geometries. Normally while modelling any system, all the inputs and characteristics of the components should be considered. But the authors have not considered the effect of viscosity on flow rate, variation in critical pressure ratio, inflow and outflow differences, Reynolds number and mass flow rate. Hence the model developed by them as a square root model does not give a very good fit.

Other researchers (Schepers, 2012) in their paper have modelled switching valves in order to study and analyse the behaviour. The paper discusses the technology developed for the characteristics of such valves, study of their dynamic behaviour, and valve analysis. The varying modes of operation, when quick switching control signals are applied, are described and discussed. A comparative study of the model when applied in closed loop simulations is done with state of the art models. The authors have conveyed in their paper that obtaining a reasonable accuracy in the model is difficult because of the quick switching action of valves. Hence, they have proposed an optimum accuracy model of valve behaviour.

Other authors (Cui, 1991), in their paper on a high speed on/off valve have talked of a rotary single stage quick digital valve. Normally rotary type valves are rarely used in fluid power systems. But in certain applications, when used, control of such valves yields transient responses. This may create peak pressures and surges resulting in resonance which has to be dampened.

The work by certain other authors (Norgard, 2015), on the modelling of electromagnetic actuators is done as a comparison between analytical and finite element modelling. It is widely known that D.C. valves take step inputs are on-off type and electromagnetically actuated. Though the researchers have developed mathematical models based on analytical and numerically based finite method, it is felt that a complete Multi physics model should be developed of the electromagnetic actuator comprising of electric, magnetic and mechanical domains. This would give the complete characteristics of the electromagnetic spool or actuator including the transient valve spool response to an input, due to fast opening and closure of the valve.

In yet another work (Zeng, 2015), by the researchers on priority type on-off digital valve, a model has developed using AMESIM software to study the characteristics of proportional control valves using PWM control. The results have indicated that the opening of the valve i.e. the time the valve spool takes to open, tends to increase with the duty ratio of the input voltage signal to the spool. In other words, this means that the main spool displacement is directly proportional to the cycle number of the PWM signal. But in order to study the performance of the valve, the spool displacement has been approximated as a linear movement with time, proportionate to the input signal. But in a practical situation, it may not be exactly so, hence a Multi physics real-life situation with effects like dead b and, hysteresis etc. will have to be modelled to give a clearer understanding of the valve characteristics.

Optimization of Digital Valve Control: The authors (Huova, 2010), in their work on optimal control systems, have developed a fault tolerance system for testing the controller used for a set of valves in parallel to drive an actuator. The idea is to test a controller known as an optimal controller, which when faulty, an alternate safe controller can be used to test the system. Such optimal controllers are designed to minimise power and tracking error. The layout below shows the schematic of the controllers.

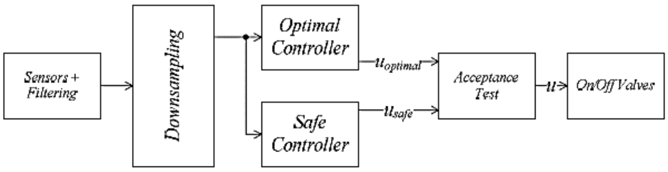

Figure.5. Block diagram of the control strategy for fault tolerancing (Huova, 2010)

The authors (Huova, 2010) claim that switching between optimal and the safe controller during motion of the actuator does not give drastic variation in the stepped input command signals. But when implemented in an actual experimental setup, changes in the command signals and desired response may occur.

The authors (Linjama, 2012), in their mechatronic design of micro digital hydraulic valves have modelled on/off valves for predicting their performance. The difficulty in predicting their performance is due to the fast switching action from fully open to fully close. There is no intermediate position. Also the flow due to a large volume of liquid is suddenly stopped. This may lead to water hammer like effect, which would be difficult to implement in the model. The researchers (Linjama, 2012), have obtained a reasonable accuracy in prediction of the flow characteristics of various on/off valves with different valve-orifice combinations. The authors have to take into account the Reynolds number, the volumetric flow rates in order to include viscosity, varying critical pressure ratio etc.

2. CONCLUSION

The current researches in the digital hydraulics have concentrated on control systems, on-off valve characteristics and controller optimization of the on-off type valves. The results obtained from the reviews are asunder:

a) An important conclusion obtained from the above review papers is that at low velocities, since control of on-off type valves is difficult, PNM (Pulse Number Modulation) is a better option than PWM (Pulse Width Modulation) type of control. This also means that if the valve characteristics are correctly predicted then controlled performance can be obtained.

b) Since there is sudden closing and opening of valves, transient pressures occur resulting in resonance, which may need damping.

c) Multiphasic modelling of dead band, hysteresis etc. in the valves is necessary to ascertain proper valve performance.

d) Development of fault tolerant controllers needs experimental setups to validate the idea of minimizing power and tracking errors.

e) Finally, while modelling the characteristics of on-off valves, the Reynolds number, volumetric inflow and outflow rates have to be considered for viscosity and varying critical pressure ratio effects.

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