A Review & Progress on Digital Hydraulic Pumps and Valves

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Abstract: *The main challenge in design of hydraulic circuits is to obtain desired flow rate and maintain required pressure, this is accomplished by using various types of hydraulic valves and other hydraulic elements. In this review paper work carried out by authors on valves with special emphasis on Digital Valves and Digital Hydraulic Power Management System (DHPMS) is presented. Digital valves are state valves (ON/OFF Valves), these valves give better control at low speeds. The state-of-the-art methodologies like inverse techniques, and use of commercially available software packages seem to make great impact on research.*

Keywords: *Digital fluid Power, Digital Hydraulic valves, Digital Hydraulic Power Management system*

1. Introduction

Digital hydraulics is an evolving field. Digital fluid power is briskly achieving a status of potential and sought-after technology for fluid power control. The reasons for use of Digital Fluid systems are encouraging because it presents exciting new solutions such as switching converters and Digital Hydraulic power management systems. Digital Displacement is a fundamental advance in field of fluid power, it is a promising technology which significantly improves efficiency and controllability of hydraulic pumps and motors.
As a technology it comprises many discrete valued components however essential feature of digital systems is its intelligent control [1]. Digital Fluid power systems is divided into two branches Parallel Connection and Switching Technologies. In parallel connection response is controlled by changing the state combination of components whereas in switching technologies output is controlled by pulse width ratio.

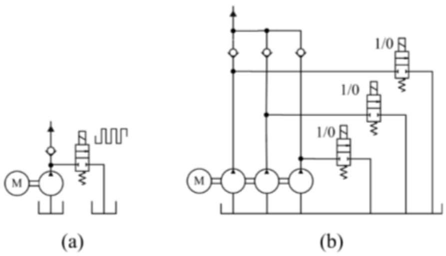

Fig. 1. (a) Switching pump; (b) parallel connected pumps [1]

2. Digital Displacement Pumps

Ehsan et al [2] the authors have used time domain modelling of pump-motor system to predict the performance under variable-demand, variable-speed at different control modes. The authors describe a new technique of digital-displacement to transfer energy between mechanical and fluid power. The digital-displacement pump-motor system is compatible with microprocessor which permits use of advanced control logic. These units are found to be more efficient than their conventional counter parts. The authors have discussed control techniques and basic algorithm which enables the controller to make a decision. The authors have concluded that the units are fast enough to achieve pressure control despite variable demand or variable speed. A schematic diagram of digital displacement pump-motor is shown in figure 2.

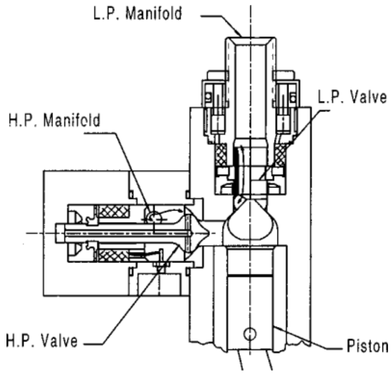

Fig. 2. Cylinder head arrangement of a digital-displacement pump-motor [2]

Wieczorek and Ivantysynoa [3] have used a CAE tool named CASPAR (Calculation of Swash Plate Axial Piston Pump/Motor) for design of hydrostatic machines. Caspar is developed at the Institute for Aircraft Systems Engineering of the Technical University of Hamburg-Harburg. It is a stand-alone tool developed using C++. It considers the time-dependent change of gap height, interaction between machine parts. There is also a module to incorporate spherical valve parts. CASPAR is designed to handle macro-geometry alterations. It presents the user with a GUI to accept inputs files, the inputs like oil properties, temperature, and machine geometry can be controlled, various types of outputs from pressure and gap flow modules can be obtained. A disadvantage of CASPAR is that it focuses on swash plate and axial pumps. To analyze gear pump performance another tool named HYGESim (Hydraulic Gear machines Simulator) can be used.

3. Digital Hydraulic Power Management System (DHPMS)

The conventional solution to meet power requirements is use of pumps and motors connected suitably in the Hydraulic circuit, but this not only increases the complexity of the circuit but also increases the installation and maintenance costs.
Digital hydraulic presents a new approach to meet the power demand. In DHPMS a centralized pump-motor transformer with many independent outlets is used. This approach greatly simplifies the mechanical design. The system variables pressure and flow can be controlled independently and there is no limitation on the pressure amplification which can be used for high pressure applications. In DHPMS flow is possible from prime mover to outlet, from one outlet to another outlet in any direction.

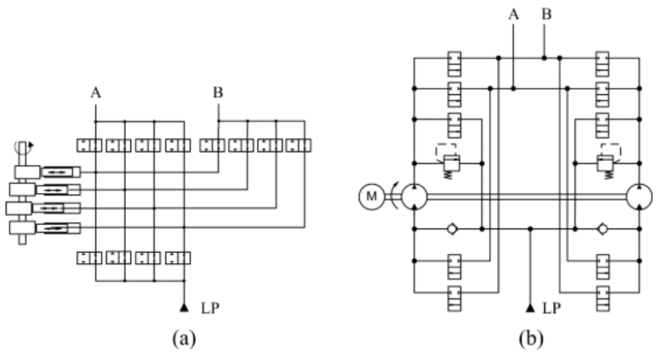

Fig. 3. (a) Two-outlet piston type DHPMS; (b) DHPMS based on fixed-displacement units [1]

4. Digital Hydraulic Valves

In digital hydraulic systems solenoid operated directional seat valves are used to control system variables namely pressure and flow. The valves have two possible states ON or OFF. A distinguishing feature of digital valves is that they are able to perform all valve functions such as pressure regulation, direction and flow control by using only ON/OFF type valves unlike traditional hydraulic system which utilize different type of valves to perform different functions. A group of ON/OFF valves connected in parallel make a Digital Flow Control Unit (DFCU) and at least 4 of

such units are required to substitute a proportional valve. In digital hydraulics circuit there may be numerous control lines. These control lines are independent and the ability to control each edge independently provides better control. This not only reduces power loss but also enables precise control. An additional advantage is that seat valves have zero leakage as opposed to traditional proportional valves. In digital hydraulics each valve needs to be controlled individually this results in a large number of possible valve combinations but it increases the complexity of control algorithm.
Conventional Servo valves are highly reliable hydraulic components that exhibit good response when compared to ON/OFF type valves, but when the spool gets stuck in one position a high frequency jitter has to be used to bring it back; When the same problem is encountered in ON/OFF valves a lesser technology and thus less cost is required to retract the spool [4], hence ON/OFF valves are used in digital valve technology. These valves are often used in slow moving loads and fast switching times.
Digital valves provide better control on pressure applied for precise control or movement of the machine elements. This is achieved by a bank of ON/OFF valves. These valves also simplify the architecture or circuitry by integrating the functions which were performed by proportional valves. The valves are controlled through a software. There could be many miniaturized valves in a digital bank, to accommodate these valves a manifold may be designed. The benefit of these valves are energy efficiency, speed, durability, accurate movements of elements and low initial investment.

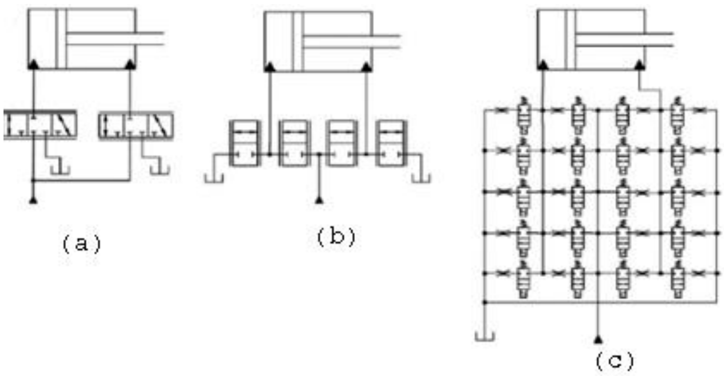

Fig. 4. (a) 2-three-way proportional valve distributed system; (b) 4- two-way valve system; (c) a digital on-off valve system [1]

5. Literature Survey

Linjama [1] presents two implementation approaches of DHPMS one using reciprocating piston unit and the other using fixed displacement unit. A piston type DHPMS is similar to switching system because continuous valve switching is needed. A DHPMS based on fixed displacement unit is a true parallel connected system and no valve switching is needed to maintain any flow combination of outlets. Fixed units provide better controllability because each fixed unit can have different displacement this in turn allows control on flow rates, but controlling pressure is challenging as only certain values are available. It is not possible to maintain pressure at target value; however, pressure can be driven towards target values leading to fluctuation in pressure around target values. In order to maintain hydraulic power author suggests certain strategies such as using more fixed displacement units to increase resolution of flow rate, maintaining correct average flow rate and pressure by using switching between two closest flow rates this can be achieved by using distributed valves together with DHPMS. A high-pressure accumulator can be used to meet peak power requirements. The salient feature of DHPMS is that it can fully utilize the energy storing capacity of accumulator. The efficiency achieved through DHPMS is reported to be much better than traditional approach.
Payne et al [5] have studied the application of digital displacement technology for wave enegy conversion. The technology is mainly based on radial piston layout. It provides faster response than conventional machines. The authors have analyzed the response of system for step up and step down command and investigated the change in flow rates. The efficiency of digital

displacement was about 90% where as for bent-axis machine it dropped to 80%. In the study it was found that digital displacement was well suited for wave energy conversion.

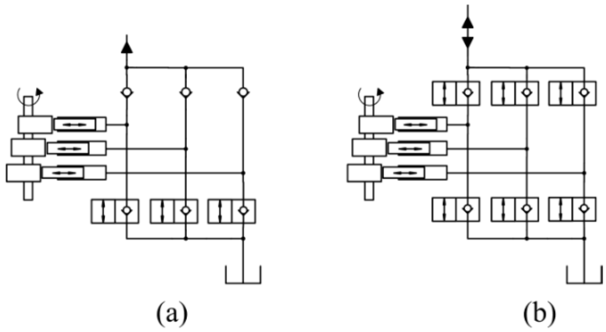

Fig. 5. (a) Piston type digital pump; (b) pump-motor [1]

Gradl and Scheidl [6] have suggested the application of Pulse Frequency control system instead of conventional Pulse Width Modulation system the authors have modelled the dynamic response behavior of systems. Authors have investigated control strategies in digital hydraulics using pulse Frequency Control (PFC) and pulse width modulation (PWM).

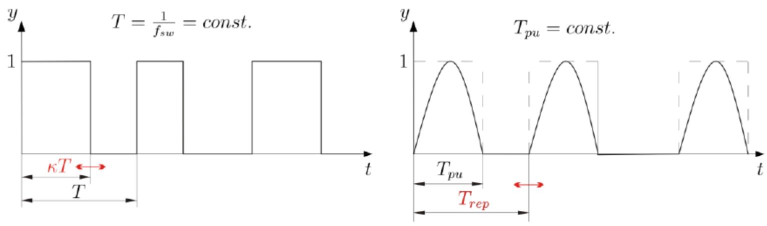

Fig. 6. PWM (left) and PFC (right) and their characteristic values [6]

In PFC input is applied in the form of a flow pulse to a digital flow unit such as a digital pump only after the previous pulse is finished. In PFC the pulse quantity and maximum repeating frequency are fixed. Theses pulses may interact with the plant and hence the whole plant needs to be analyzed.

Palonitty et al [7] have studied the feasibility of pulse frequency modulation to improve controllability of equally coded valve system at velocities below minimum velocity of Pulse number modulation (PNM) control. The authors have extensively conducted experiments to measure improvement of the PFM method on tracking the control performance. It was reported that simultaneous control on pressure and velocity is not possible, authors used a single cylinder drive in two edge connections. The authors have also discussed the challenge of accurate position tracking at low velocities using digital hydraulic valve control and suggested using a greater number of valves or to use 4-edge control and exploit cross flow. The PFM may be used to track control at low velocities and conclude that PFM can be used to improve controllability at least of single acting cylinder.

Sell et al [8] report development of a valve that combines high flowrate and switching speeds required for switched Reactance Hydraulic Transformer (SRHT)

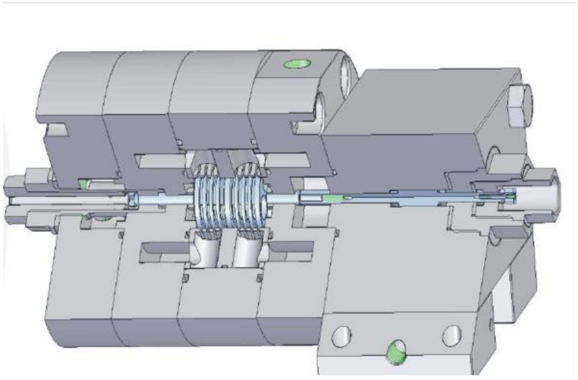

Fig. 7. CAD model of the fast switching linear valve [6]

Yang & Pan [9] have studied recent developments in the field of hydraulics especially in China. The authors enlist the future trends and discuss the challenges and recommendations in fluid power. The main challenges include its efficiency, compactness, and environmental impact. The authors present hydraulically driven robots and machines namely BigDog, Hydraulic Quadruped (HyQ), qRT-2, Baby Elephant and John Deere's walking harvester. The author concludes that in spite of the challenge there is a very promising future for fluid power.
Liu et al [10] carried out research using proportional relief valve and reported that steady state error can be reduced by dynamic positioning. A conventional PID controller is used in closed-loop to control the pressure. The authors discovered that the system flow does not affect the actual pressure in closed loop system. The variation in actual pressure and set pressure for various input signal is discussed, for step and ramp signal actual pressure can be adjusted to set pressure and for sine and ramp signals actual pressure fluctuates around set pressure.
Dasgupta and Watton [11] have used the bond-graph technique without linearization. The pressure setting is achieved by current-controlled proportional solenoid or by pilot-spring pre-compression. A bond-graph model of proportional solenoid controlled piloted relief valve and various mathematical equations have been presented in the paper. The developed model takes into account laminar and turbulent flow through valve ports. Symbols 2000 software is used, it incorporates a facility called Encapsulation. Sub-systems called as capsules can be created in the software for additional control. The experiments reveal good agreement between calculated values with 95% confidence level. Transient response uncovers the increase in working range of hydraulic systems where such valve is used. The authors conclude that pre-compression of pilot spring and diameter of damping orifice are important design variables.
Pindera et al [12] the authors have used Co-Simulation to analyze the system. In Co-Simulation a complex multi-component system can be analyzed by further dividing it into sub-systems and components, it is well suited for analysis of Digital systems. The success of this is based on effective and efficient data exchange and communication among the modules. These are achieved by using middleware called as CoSim and CORBA protocol. A 2-way axisymmetric Hydraforce SV08-20 valve is used. The model is divided into sub-models like solenoid, fluid dynamic and dynamic motion sub-models which consider three types of forces acting on the poppet. These sub-models are intended to take into account electromagnetic force, inductance, flow-force, friction force, spring force and valve gain. The forces responsible for piston motion are also studied. As a result of this motion 5-piece of data is generated from position of piston and pressures from upper and lower cylinder chamber. The control is accomplished through Bang-Bang Standard (BBS) controller and Bang-Bang Model Based (BBMB) Controller. The authors have proved that Bang-Bang control strategies can track a square wave in non-oscillatory manner. The errors were less than 3%.

Heikkilä et al [13] have studied a mobile boom. The boom is slightly modified i.e. bucket is replaced by a mount to incorporate different weights required for the study. The pressure and displacement control using DHPMS, proportional and digital valves is delineated in the paper. The authors have considered different combinations of pumping and suction for selection of a combination in which the pressure error is minimum, further for displacement control the volume errors in the cylinder chambers should be minimum. To calculate volume errors the geometric piston development along with compressibility of the fluid has been considered. A control algorithm is used to control the cylinder back pressure. The control performance of DHPMS is studied for proportional controlled and direct displacement controlled system. The authors conclude that DHPMS is suitable for displacement controlled systems, however, if small number of pumping pistons with insufficient displacements are used controllability at low velocities is difficult. The authors report 50% energy savings was achieved by using direct displacement control when compared with proportional ELS control.

Vukovic and Murrenhoff [14] the authors have emphasized on holistic design methodologies that not only increase the energy efficiencies of the system, but also improves the system architecture. The authors are of the view that energy recovery especially in machines that involve frequent cyclic motion is important. This may be achieved through a control software.

Vescovoa & Lippolis [15] the authors have carried out axis-symmetric and 3D-analyses on Directional Control valve. In the study the flow is separated by zones, a zone near to walls of the valve and another zone in the center of flow; this is known as "Two Layer Zonal model". This model uses damping functions and classical turbulence model RNG K–ε. In axis-symmetric analysis, velocity and pressure contours are plotted. It is observed that in restricted section where pressure energy is converted into kinetic energy there is abrupt variation in acceleration. The velocities in the zones are found to be different, it is characterized by a high velocity zone at center surrounded by a very low velocity zone. A gradual deceleration at the core is caused because of interaction between the zones this also results in great shear forces, however no appreciable pressure recovery is reported. The authors have proposed a new parameter viz. equivalent hydraulic diameter, it is a non-dimensional parameter that considers flow force and flow rate. The authors have discussed the effect of pressure drop on various parameters like discharge coefficient, K-parameter (average static pressure acting on single spool face), flow coefficient have been studied. The velocity and pressure contours for sufficient meridian planes are plotted to obtain a complete image of three-dimensional field. In comparison it is observed that the axis-symmetric model does not consider circumferential pressure loses and lays more importance on velocities in metering sections, whereas 3D model reveals greater radial velocity than axis-symmetric model. It is clear that 3D model considers various parameters which were not considered by axis-symmetric analysis. 3D model gives a comprehensive means to understand the flow, pressure distribution and its effect.

M. Erhard et al [16] the authors have applied FEM and DOE approach to predict the geometrical shape of solenoid. The concepts of Response surface methodology and Monte-Carlo simulations are used in this paper. The models developed using DOE are generally robust. Usually, in industries the process of development is based on trial and error basis; in this paper the authors propose a holistic simulation approach to overcome the existing gap. The authors discuss the application of inverse simulation approach which involves calculation of subsystem characteristics at component level and thus predicting the geometrical shape fulfilling the subsystem requirement. The subsystems involved are hydraulic, mechanical and solenoid subsystems, their inverse model equivalents are flowrate, solenoid current, valve displacement and pressure. The authors have analyzed a direct-operated proportional pressure relief valve and are of the view that in geometrical valve design the concept of control orifice is important, the characteristics curves for zone, piston and sphere concepts are studied. The cone concept is favorable because the cone shape facilitates smaller actuator design. Various other force characteristic including spring forces are also studied. The results agree well at low pressure. In measurement and simulation, it was observed that material properties are deciding factors in solenoid design. The verification of hydraulic sub-system design is done through optic measurement and displacement of armature is done by laser vibrometer. The authors conclude that measured and simulated results are in good

agreement. Robustness analysis reinforces and ensues the same. Inverse simulation approach supports virtual product development.
Digital displacement has become the heart of Industry 4.0. Artemis a world leader in Digital Displacement technology. According to Artemis, “A new generation of digitally enabled smart machines is transforming industrial processes” [17]. Digital Displacement pumps (DDP’s) offer improved productivity at reduced costs, pressure, and energy loses. DDP’s respond to load changes rapidly than conventional hydraulic machines.
Artemis is working with major aircraft OEM’s to determine potential for replacement of conventional hydraulic pumps by DDP’s. DDP’s can be used in ground based and distributed propulsion applications like flight simulators, fatigue testing rigs and heavy lift quadcopter. Artemis has conducted field tests of 16-ton excavator fitted with DDP’s instead of conventional standard axial-piston pump. It was observed that fuel consumption was reduced between 16-21% and productivity increased by 11-12%, the company estimates that Digital Displacement technology will reduce fuel consumption by 50% resulting in significant reduction in engine size. Artemis and Quoceant are working on a project that concerns with making electricity from waves. They have developed a technology called ‘Quantor’ which includes use of digital displacement hydraulics.

6. Conclusion

Digital Hydraulics is a relatively new field of research with promising and application-oriented solutions. Digital pump-motor, transformers, multi-chamber cylinders and DHPMS are some of the newer trends of digital fluid power all of these promise better energy efficient solutions. A disadvantage is the commercial unavailability of valves and valve packages. The application of DOE, inverse techniques and the advanced software packages enable calculation of various parameters that were difficult to calculate previously. These developments in various domains are taking research to a new level and aimed at improving the productivity and yield better energy efficient solutions.

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