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CHARACTERIZATION OF AN EFFICIENT DIGITAL HYDRAULIC SYSTEM

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Abstract: *The characterization of a digital valve system is discussed in this paper. Four flow paths are used to control a double acting cylinder independently by using parallel on/off valves, a path to control each side of actuator, tank and pressure sides, each digital flow control unit (DFCU) consisting of five 2/2 on/off valves. The aim of this paper is to discuss the energy efficiency of this system by combining the digital and IMV systems. Flow capacities of valves are set according to binary coding which is to powers of two. The pros of IMV and digital systems are combined to improve the hydraulic systems' performance and to reduce power consumption and losses. Moreover, a control system is implemented to best get advantage of IMV and digital systems. Traditional proportional flow control valve has a spool to meter flow between the two sides of cylinder, pump and tank, valve is only suitable for one application. In this system many applications are suitable with different control techniques. An additional energy saving method which is the energy efficiency using a variable displacement pump. The main points to be discussed, 1) IMV and digital hydraulic advantages over traditional proportional system, 2) feasibility of combining all these energy saving methods together. The aim is to implement an efficient system with the minimum power consumption and to select the best control (won't be discussed in this paper) to achieve it.*

Keywords*: Digital hydraulic, Independent Metering Valves, Energy saving, on/off valves*

1. Introduction

The key idea is to use simple binary components and intelligent control algorithms to produce a digital equivalent to the analogue proportional- or servo valve as discussed by Arto Laamanen et al. [1].

The DVS (Digital Valve System) discussed in this paper consist of 4x5 on/off-valves which results in 220 state combinations. Five valves give good enough controllability for most applications and thus the total number of valves is typically 20. Independent metering valve realized by digital control edges consisting of parallel connected on/off-valves. Flow areas of the control edges are completely independent in the digital valve system and the valve system can implement different control modes together with simultaneous velocity and pressure control [3]. In proportional valves the spool geometry is normally in hardware and cannot be changed during operation, in digital valve this can be done when all of the four control notches are independently controllable, the valve is capable of changing the operation mode from inflow/outflow to differential mode, or vice versa. Some of these modes are regenerative. Serial Connection, Kato and Oshima [5] introduced the concept of the digital small stepping method and studied the effect pressure difference, volume size, oil temperature and cycle frequency on the step size. Parallel connection, valves in parallel give stepwise controllable velocity that yields higher maximum velocity, smaller pressure transients and better accuracy [1].

Coding determines flow rates of valves of DFCUs expressed relative to the smallest valve. Some coding schemes are binary coding (1, 2, 4, 8,16, … , 2N−1), Fibonacci coding (1, 1, 2, 3, 5, 8, … , PN−2+ PN−1) and Pulse Number Modulation (PNM) coding (1, 1, 1, 1, … , 1). The system in this paper uses binary coding, the inary-coded DFCU is similar to DA converter and output has 2N discrete values depending on which valves are open. On/off valves are not expensive, reliable, and not affected by contamination and possibly zero leak. Independent metering reduces metering losses and thus, energy consumption. Servo or proportional valves have good controllability but they give many problems, such as cavitation (To avoid cavitation and good efficiency call SMISMO control that is impossible with standard spool type valves), high power losses, sensitive to contamination and high price. The on/off control is associated with many negativities such as noise, pressure rise, jerky motion and poor controllability motion control with slow-response valves, improved idleness and reduced durability necessity, when compared to PWM way. The response time is not critical in these applications and slow response is many times advantageous in order to reduce pressure peaks, energy efficient motion control is possible with slow-response on/off, valves Matti LINJAMA and Matti VILENIUS [2]. Plurality of similar components makes digital systems redundant, for example, failure in single valve causes only a reduction in performance not the system to fail or stop[4].

Digital components are also easier to optimize for performance because there are no requirements for linearity or hysteresis. Digital component is either ON or OFF but nothing between. Challenges of digital technology are large number of components and/or risk for jerky control. The control problem of the digital valve system is: “Select the best possible control combination of the valves at each sampling instant”. Two basic problems are how to define integrity of a control combination and how to find the best one. Good controllability requires proper design together with sufficient number of components or extremely fast components. Digital systems have always been more expensive at the beginning but mass production has made them cheaper than analogue counterparts. The control of traditional valves is simple because the control signal and spool position are closely related. The drawback is that only predefined control modes are possible and that pressure level cannot be adjusted because of the fixed ratio between flow areas [9].

In fixed displacement pumps the quantity of displaced flow by each pump shaft rotation cannot be altered. The pump's displacement is changed by varying pump’s speed. Since industrial hydraulic systems usually use invariable speed electric motors as main movers, fixed displacement pumps do not find many applications. In case of fixed displacement pump, the actuators need changing flow rates during operation so these pumps must be sized to deliver the maximum flow required. But unfortunately, when less flow is required, the extra flow from these pumps must be dumped over the system relief valve at maximum system pressure. This process converts the unnecessary energy into heat. For this reason fixed displacement pumps should only be used in constant speed applications or in systems where speed control is of short durations. Important issue is the best use of available energy resources. Using energy-saving, variable displacement pumps has contributed to overcoming that hydraulic systems are by structure not efficient. These variable displacement pumps only give flow when needed and as required. Variable displacement pumps cancel the need for flow control and pressure reducing valves.

It is necessary to use a separate control of the two fluid streams to minimize the throttling losses. The independent metering valve (IMV) concept has lately attracted interest since IMV uses a mix of multiple electro-hydraulic poppet valves (EHPV) and thus enables flow regeneration by switching among several metering modes. Another feature of IMV that EHPVs constituting IMV are electronically controlled contributes to energy efficiency through precise flow control and fast response. Load-sensing hydraulics used in mobile machinery have very low efficiency could reach low as 4% [6]. Successfully the energy losses of a wheel loader were reduced by using a digital hydraulic valve system (DVS) as an alternative for traditional Load Sensing system [7]. More efficient system could be attained by using pressurized tank line [8]. High performance digital hydraulic force, velocity and position tracking control solution has been experimentally validated [10].

2. Modeling and simulation

The system that will be discussed is depicted by the schematic diagram of fig.1

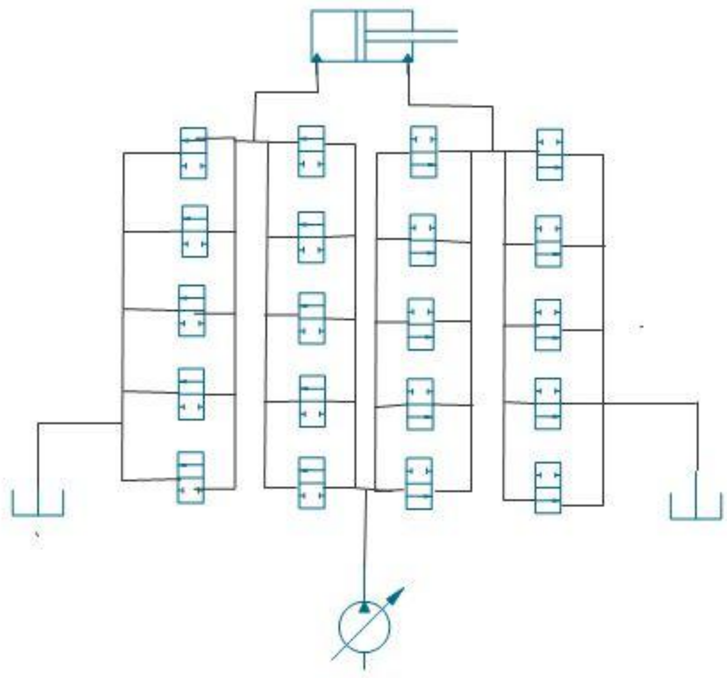

Fig. 1 system schematic diagram

The model consists of four control paths; each includes five parallel connected on/off valves. A variable displacement pump is used to help achieve the target high efficiency system, the metering modes that are discrete metering modes where valves provide a flow path and switching to another mode involves closing a valve and opening another to provide for a different flow path.

At constant load and fixed pump displacement, Low pump revolutions, velocity maximum actuator and lowest energy when PA fully opened & BT fully opened, velocity minimum actuator with highest energy at PA 2 opened & BT fully opened. Increasing pump revolutions, maximum velocity actuator increases with same findings as highest energy at minimum velocity actuator at PA 2 opened & BT fully opened and lowest energy at PA fully opened & BT fully opened. At pump max revs., maximum velocity actuator and lowest energy when PA fully opened & BT fully opened, minimum velocity actuator with highest energy at PA 2 opened & BT fully opened. Minimum velocity actuator not affected by pump revolutions as it remains constant regardless of pump rpm, lowest energy at any state except lowest pump revs. as energy slightly lower. At low pump rpm, maximum velocity of actuator could be achieved with three different states at same pump speed but with higher power consumption when increasing throttling, all by valves' switching.

Same actuator velocity could be achieved with different techniques at same pump speed as well as different pump speeds using different valves' switching. At same pump speed, highest actuator velocity is achieved when all valves in upstream side are open and downstream side also opened which mean highest pump flow rate, as long as upstream side DFCU's valves are all opened pump flow rate is max. at that pump speed but power consumption differs depending on downstream side DFCU's valves states. When pump speed increases, Vmax actuator increases and also pump flow rate with less actuator stroke time.

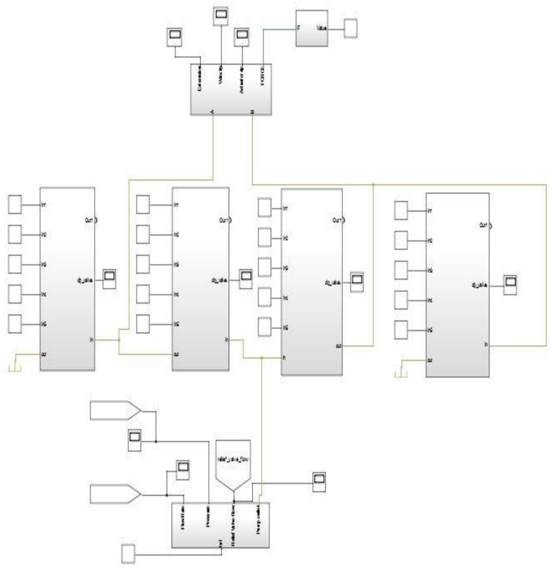

Fig. 2 Full system Matlab model

3. Discussion and results

Three cases are discussed in this paper. First case digital valve system with four DFCUs, second case digital valve system same as first system but largest orifices have been removed to decrease pressure drop over DFCUs, hence, power consumption decreased as a result, third system is a common proportional valve system. The idea behind using separate meter-in separate meter-out system (SMISMO) is achieving both pressure and velocity control. Velocity control by switching outflow side DFCU's valves and pressure compensation by inflow side DFCU's valves switching.
All three following cases achieve same velocity and extension results to be able to compare between them from different point of views.
The following figures show the power consumption (Y-axis) as function of time (X-axis) in different states depicted by the following figures. The first figure, the digital valve system where all valves are set according to binary coding as discussed before, shows highest power consumption of all three states where the pressure drop is the highest as well. Second figure, depict same digital valve system but with a modification that is, excluding the orifices in the fourth and fifth valves' lines to decreases pressure drop, hence power consumption decreased as a consequence. Third figure shows proportional valve system with lowest power consumption between the three states, only small difference in comparing with no orifice digital valve system (system depicted by figure 2). Working on the efficient digital valve system which mentioned by second case, to get the most out of SMISMO technique by first switching upstream valves pressure compensation is achieved but power consumption slightly increased.
The digital valve system with separate metering shows a great potential of further lowering power consumption even better than proportional valve system, by increasing number of parallel connected on/off valves and selecting the best control to achieve optimum result and to get the most advantages of this power saving digital valves system over the proportional valve system.

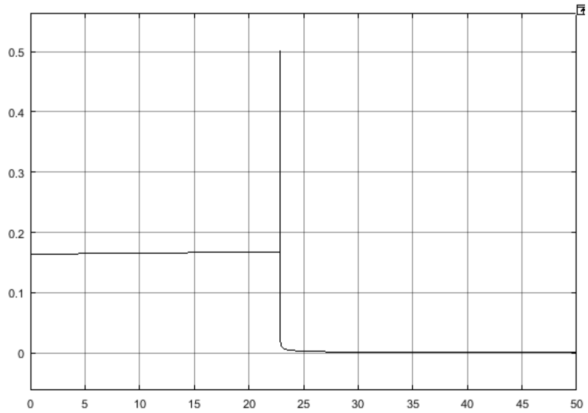

Fig. 3 With orifices

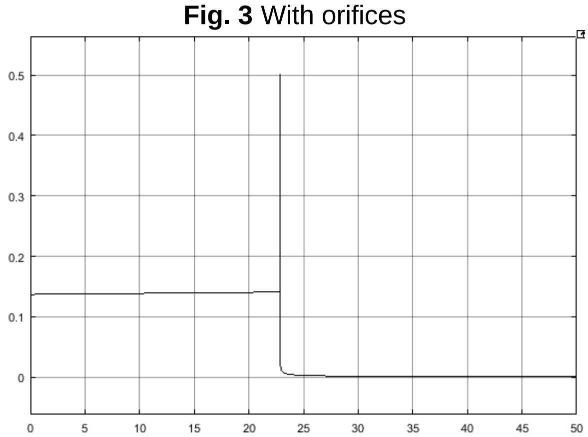

Fig. 4 Without orifices

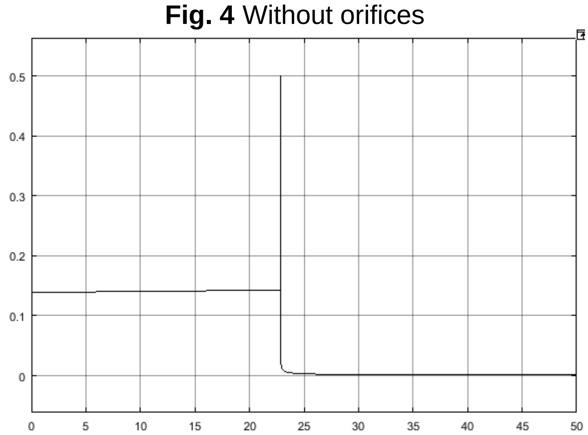

Fig. 5 Proportional Valve

A comparison table 1 is best to decide whether the digital valve system a potential power saving method or not. All three systems achieve same stroke time with same load, which means same target to select best system by least energy consuming. The table compares between the three systems discussed previously from three points of view which are pressure difference over pump, pressure difference over upstream DFCU or upstream side in case of proportional valve system, and energy consumed.

Table 1 : Comparison Table

System	dp_Pump (bar)	dp_Valve (bar)	Energy consumed (KJ)
Digital Valve_1	20	3.6	3.8
Digital Valve_2	16.5	0.59	3.2
Proportional Valve	17	0.85	3.3

By observing the comparison table, it is clear that at same conditions digital valve system_2 showed a great power saving potential and even better than proportional valve system, especially by applying new control solutions will increase power saving greatly, which will be discussed in next paper. This paper was mainly intended to study only mechanical behavior without any control solution.

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