

DIGITAL FLUID POWER – STATE OF THE ART

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ABSTRACT

Digital fluid power technology has rapidly achieved the status of potential and serious fluid power technology. Several research branches exist each having their own strengths and challenges. Applications are also emerging. This paper summarizes the research results so far and tries to find development trends and estimate the future of digital fluid power.

KEYWORDS: Digital hydraulics, digital pneumatics, digital fluid power

1. INTRODUCTION

In October 2010, the third workshop on digital fluid power gathered together 115 people from seven countries, which is clear sign of growing interest on digital fluid power technology [1]. As the technology is new, its characteristics, benefits, challenges, and scope are widely unrecognized. This paper gives an overview of the technology.

1.1. Definition of Digital Fluid Power

The term “Digital Fluid Power” is broad and not fully defined. In general, a digital system has *a number of discrete valued components*, some examples being a microprocessor (transistors), a digital camera or display (pixels), a book (letters) and DNA (acid pairs). The essential feature of digital systems is also intelligent control, such as display driver or writer. A two-valued single component without any intelligence (e.g. flashlamp) is not considered as a digital system. However, the pulse-width modulated single component (e.g. electrical switching regulator) is generally considered as a digital system.

Fluid power includes hydraulics and pneumatics and digital fluid power could be defined as follows:

“Digital Fluid Power means hydraulic and pneumatic systems having discrete valued component(s) actively controlling system output.”

Digital fluid power does not mean digital control of analogue components. Some borderline cases are the control of valve spool by using stepping motor or bang-bang positioning of actuators.

1.2. Branches of Digital Fluid Power

Two fundamental branches of digital fluid power are systems based on parallel connection and systems based on switching technologies. Both can be applied in several different ways. Parallel connected systems have plurality of parallel connected components and the output is controlled by changing the state combination of the components. The system has a certain number of discrete output values and no switchings are needed in order to maintain any of them. Switching technologies utilize fast and continuous switching of single or a few components and the output is adjusted by e.g. the pulse width ratio. The application of the approaches in different hydraulic functions is discussed next. Hydraulic circuit diagrams are given by using two-way on/off valves only because it is the most general solution. In some cases, it is possible to use three-way or four-way valves in order to reduce the number of components. Pneumatic solutions are analogous. Characteristics, benefits and challenges are discussed in more detail in Chapter 3.

1.2.1. Digital Hydraulic Valves

Figure 1 (a) presents the implementation a switching controlled two-way valve. It controls the average flow area by the high frequency modulation and the pulse-width modulation (PWM) is the most common approach. In theory, the average flow area can have any value, but finite valve dynamics limits the smallest and biggest possible duty ratio. Controllability depends also on the switching frequency. Low frequency improves controllability of the average flow area, but increases pressure pulsation. Careful system design and/or damping devices are normally needed to suppress noise.

Figure 1 (b) shows the parallel connected implementation of the two-way valve. The nickname DFCU (Digital Flow Control Unit) is used for this kind of valve assembly, and the simplified drawing symbol is shown in Fig. 1 (c). The flow area of the DFCU is the sum of the flow areas of the open valves. Two factors determine the steady-state characteristics: The number of parallel connected valves N , and the relative flow capacities of the valves aka coding of valves. Binary coding is the most common method and the flow capacities are in ratios of 1:2:4:8 etc. Other coding methods include Fibonacci (1:1:2:3:5 etc.) and pulse number modulation (1:1:1:1 etc.). Independently on the coding, DFCU has 2^N opening combinations, which are called *states* of DFCU. Each state has different flow area in the binary coding while varying degree of redundancy exists in the other coding methods. Essential difference to the switching valve is that DFCU does not require any switchings to maintain any of the opening values. Switchings are needed only when the state changes.

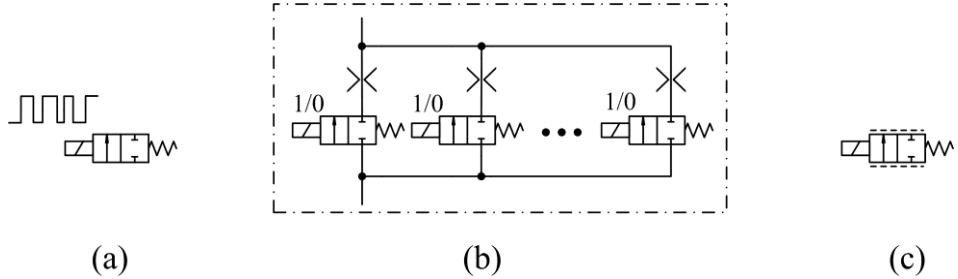


Figure 1. PWM controlled on/off valve (a), digital flow control unit – DFCU (b) and the simplified drawing symbol of the DFCU (c). Orifices are used to match flow capacities of valves in (b).

Figure 2 shows how to implement the digital hydraulic four-way valve. The approach is the same as in analogue distributed valve systems: each control edge can be controlled independently contrary to traditional four-way spool valves. However, the implementation of fast, leak free and bi-directional valves is easier in the digital world.

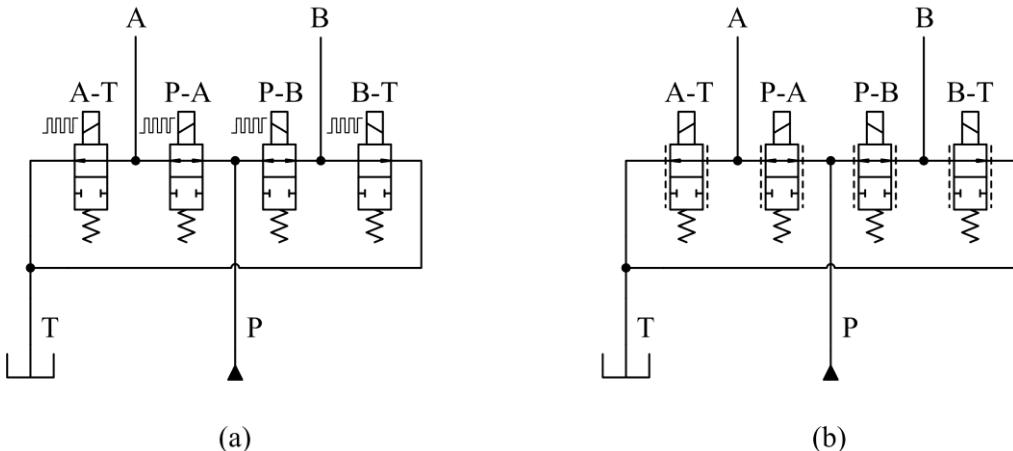


Figure 2. Implementation of distributed four-way valve by PWM controlled on/off valves (a) and DFCUs (b).

1.2.2. Digital Hydraulic Pumps

Digital pumps can be implemented similarly as digital valves as shown in Figure 3. The switching version has one fixed displacement pump and its flow rate continuously switches between system and tank. The parallel connected digital pump has a number of fixed displacement pumps on the same axis and each of them can be connected to the system or tank independently. Again, different coding methods can be used in the selection of pump sizes.

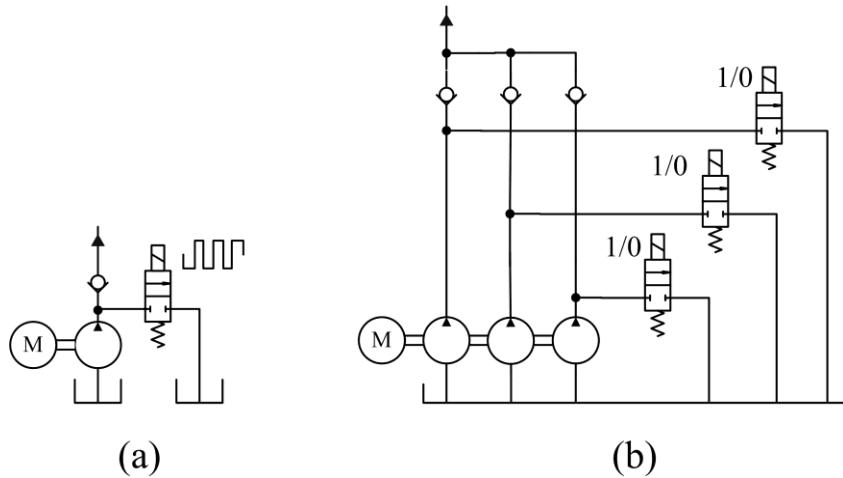


Figure 3. Switching pump (a) and parallel connected pumps (b).

Another way to implement digital pump is to control each piston of a piston pump independently by active on/off valves. An example circuits are depicted in Figure 4. The version (a) is pure pump and each piston can pump into the system or run in the idle mode. The average flow rate is controlled by the ratio of pumping and idling pistons. Partial pumping strokes are also possible. The version (b) is pump-motor and each piston can run in pump, idle or motor mode. The motor mode requires continuous switching of the control valves.

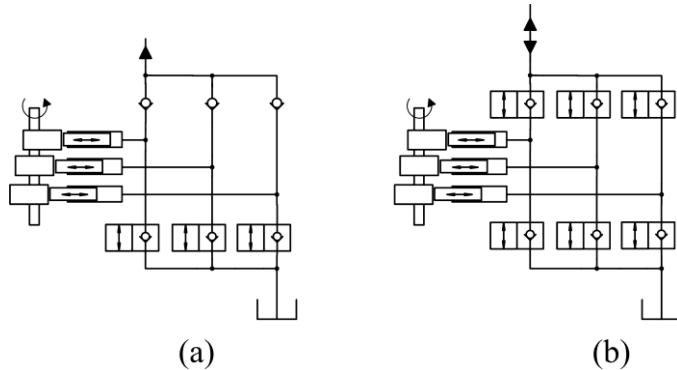


Figure 4. Piston type digital pump (a) and pump-motor (b).

1.2.3. Digital Hydraulic Actuators

Hydraulic actuator is a device, which converts pressure(s) to torque or force. Figure 5 presents implementations of digital motors, which are mirrors of digital pumps. The switching version continuously switches between full and zero torque while the parallel connected version has several independent motors on the same axis and sizes of the motors can be coded according to the system requirements. The implementations of Fig. 5 are one quadrant, and four quadrant versions are left to the exercise for interested readers.

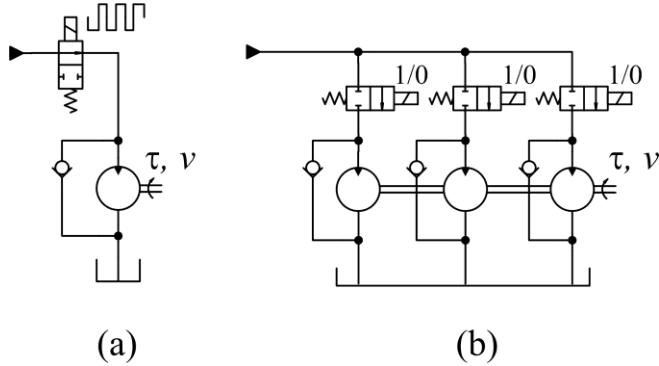


Figure 5. Switching motor (a) and parallel connected motors (b).

“Switching” cylinder is similar to switching motor of Fig 5 (a) and is not presented. The parallel connection version has many implementation options. The simplest option is to connect several cylinders in parallel (Fig. 6 (a)), but more compact design can be achieved by the integrated multi-chamber design as shown in Fig. 6 (b) and (c). Four integrated chambers is the practical maximum, which results in 16 discrete force values depending on the state combination of the valves. Further increase in the number of force values can be obtained by increasing the number of supply pressures. The number of force values is N^M where N is the number of the supply pressures and M is the number of chambers. Similarly to other parallel connected systems, different characteristics can be achieved by varying the coding method, i.e. the relative piston areas.

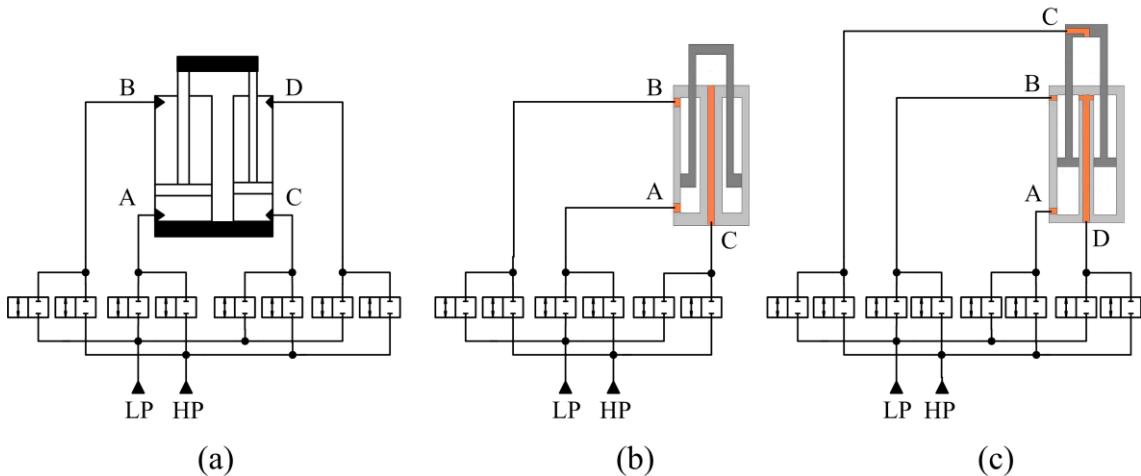


Figure 6. Different implementations of multi-chamber cylinders. LP = low pressure line, HP = high pressure line.

1.2.4. Digital Hydraulic Transformers

Digital hydraulics offer some interesting alternatives for the traditional hydraulic transformers composed of traditional pump and motor. The switching converter mimics the electrical switching converters. High frequency switching together with proper hydraulic inductances and fast check valves allows the implementation of the Buck converter, for example. Hydraulic Buck converter is shown in Figure 7 (a). The parallel connected linear transformer utilizes the multi-chamber cylinder approach and an

example is shown in Figure 7 (b). The third transformer type is discussed in the next Section.

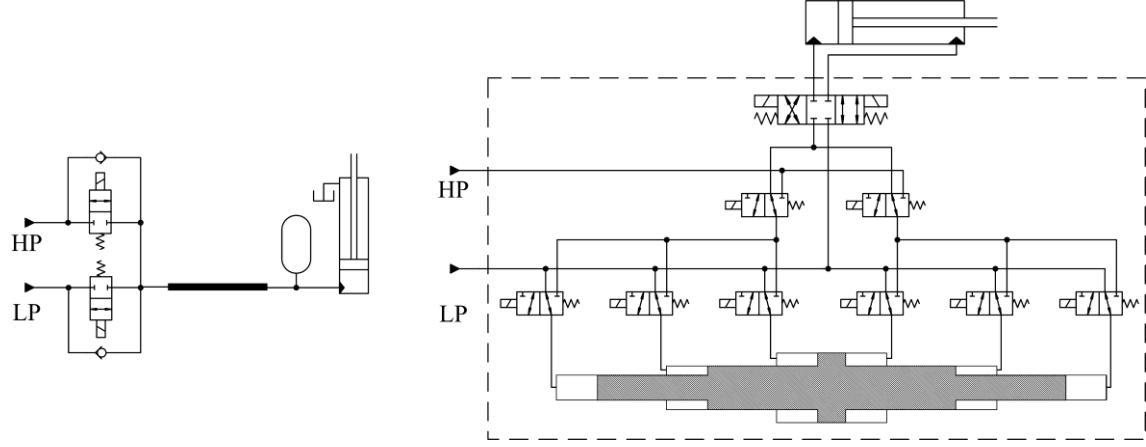


Figure 7. Switching converter (left) and linear converter based on parallel connection (right) [2].

1.2.5. Digital Hydraulic Power Management System

Digital hydraulic power management system (DHPMS) is a new solution, which consists of one integrated displacement machine having a number of independent outlets. Pressure and flow rate (including flow direction) of each outlet can be controlled independently and pressure transformation happens automatically. There is practically no limitation for the pressure amplification, which allows the full utilization of accumulator energy storing capacity. A drawback of the machine is its centralized nature, which means long hoses in many applications. Figure 8 shows two ways to implement DHPMS. The piston type DHPMS is an extension of the digital pump-motor of Figure 4 (b). The other version uses fixed displacement pump-motors.

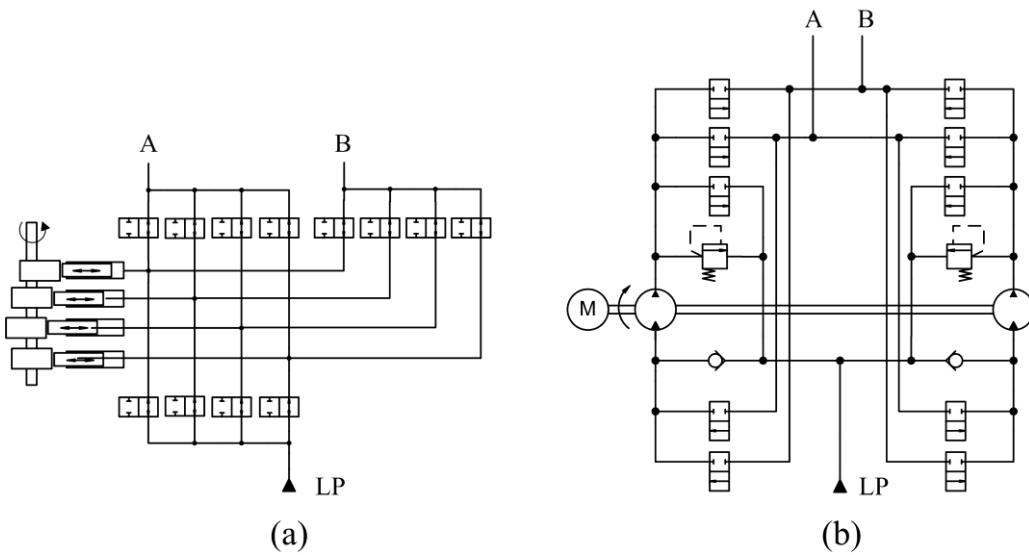


Figure 8. Two-outlet piston type DHPMS (a) and DHPMS based on fixed displacement units (b).

2. HISTORY AND STATE OF THE ART

This chapter shortly introduces the development and research on the field of digital fluid power. It is clear that the list of references is incomplete because it is hard to find especially the older research papers.

2.1. Pre-Computer Time

Parallel connection principle is very old. An example of this is the London Hydraulic Power Company, which started the setup of water hydraulic power distribution network in 1883. The typical pumping station consisted of six steam engines and the output power was adjusted both by the speed of engines and the number of running engines. The control principle was simple: when the weight of the weight-loaded accumulator dropped low enough, the operator started the next engine. The system was the largest hydraulic system ever built and had 296 km of 5.5 MPa pressure line and 7.5 billion liters of annual output in the 1930s. [3]

An on/off switchable piston pump has been presented in the Aldrich's patent in 1920 [4]. The pump can be enabled and disabled by the mechanism, which either allows the normal operation of the suction valves or keeps them open all the time. This is close to the digital pump of Fig. 4 (a) with the exception that pistons cannot be enabled or disabled independently.

The idea of using several hydraulic valves in parallel is probably as old as the use of hydraulic valves. An early reference is Rickenberg's patent in 1930 [5] consisting of three solenoid valves each having different flow capacity. General four-way digital valve system of Fig. 2 (b) has been presented in the patent of Murphy and Weil in 1962 [6]. Virvalo [7] used one DFCU for controlling the velocity of a hydraulic cylinder already in 1978. As the computer control was not available, the control logic was implemented by a resistance network circuit. The switching control has also been applied without computer control. The pulse frequency modulation control of the anti-slip brake is an early example [8].

It can be concluded, that the digital fluid power was hardly used in the pre-computer time. Main principles were invented but wider application was difficult. Another reason was the invention of servo and proportional valves and variable displacement pumps and motors, which largely removed the need for digital fluid power at that time.

2.2. Developments in Automotive Industry

The automotive industry has been a big contributor to the digital fluid power. The anti-lock braking system and electronic fuel injection were introduced in the 1970s and become popular in the 1980s. They are based on switching principle and are critical parts of the car. Robustness, simplicity and price are the key benefits when compared to the traditional hydraulics. High-pressure Diesel fuel injection has become popular in the 2000s and requirements are extreme: pressure up to 200 MPa, five valve cycles per combustion, wide temperature range, high vibration level and no valve faults allowed during the lifetime of the car. Other automotive applications are hydraulic valve trains and active suspension systems. Citroën has used digital hydraulic active suspension system in certain models from 1994, for example.

The automotive industry is difficult from the research point of view. Valves are available as spare parts only without any documentation. A wide and careful analysis of ABS valves has been performed by Wennmacher [9]. The active suspension valve of Citroën C5 was measured in [10] and the author's research group has also measured the ABS/ESR valves of 2005 Seat Leone (results not published). The experiences are that many times the automotive valves cannot be used as hydraulic valves. Usually they have coil with small ED and some strange features, such as no backpressure allowed or spontaneous closing. Flow rates are also small, but good feature is fast response time. An exception is valves developed for hydraulic valve trains, such as valves introduced in [11]. Their characteristics are close to hydraulic valves.

2.3. Switching Technology

The most widely used and also one of the first applications of the switching valve control are the ABS brakes of cars [8]. In the traditional hydraulics, the applications of switching control have been rare. One successful example is the pilot control of a mobile proportional valve [12]. Research publications can be found regularly from the mid 1990s [13, 14, 15, 16]. Another active research branch of switching technologies is switching converters. The promoter of this research is Prof. Scheidl's research group in Johannes Kepler University Linz. Different solutions have been studied [17, 18] and the state of the art is a compact device with 80 percent average efficiency and about 1 kW maximum output power [19]. A PWM pump has been studied in [20].

2.4. Parallel Connection Technology

2.4.1. Parallel Connected Valves

As described in Section 2.1, the use of parallel connected valves is an old idea but only some research publications can be found before 2000. The technology has been studied in the pneumatics [21, 22] and a commercial valve exists [23]. The valve in [23] has impressive characteristics: highly integrated structure, response time less than 1 ms and 8 bits at maximum (256 output values). The author started the hydraulics research in 2000 and currently the size of the research group is ten researchers. Early research publications introduced basic concepts [24, 25] and measurements of DFCUs build from commercial valves [26]. After that the focus has been in the model based control methods [27, 28], reduction of pressure peaks [30], fault detection and compensation [30, 31], implementation of different energy saving methods [32, 33], and improving control electronics. The use of direct operated valves with proper booster electronics has resulted in good controllability without any severe pressure peaks. The cutting edge application is the nip control of a paper machine roll, in which the digital hydraulic solution is superior in terms of price, size, control performance and energy efficiency [34, 35]. Currently, the valve research concentrates on the "second generation" miniaturized valve packs having hundreds of parallel connected valves [36].

2.4.2. Parallel Connected Pumps

Parallel connected fixed displacement pumps have not been studied much although they are routinely used in many applications [37, 38]. The Artemis company is the pioneer in

the development of the piston type digital pump-motor, which can be considered as a parallel connected system (see Fig. 4 (b)). The research and development started already in the 1980s and the first publications are from 1990 [39, 40, 41]. The current six-piston version can implement pump, motor and idle strokes as well as partial strokes for each piston independently. The author's group started the research some years ago and a three-piston pump-motor was studied in [42]. The piston type digital pump-motor research has also been started in the Purdue University [43, 44]

2.4.3. Parallel Connected Actuators

The actuator research is focused on cylinders. Resistance control of a three chamber cylinder has been analyzed in [45] and experimental results show 30-60 percent reduced losses when compared to the traditional LS system. This is significant result because constant supply pressure was used. Even bigger loss reduction is achieved by using throttless secondary control approach. This has been demonstrated with a four-chamber cylinder in [46]. Other applications of multi-chamber cylinders include press and punching machines where high speed is implemented by the small piston area and high force by the bigger piston area [47].

2.5. Digital Hydraulic Power Management System

The digital hydraulic power management system is an extension to the digital pump-motor technology. The technology is new and studied only by the author's research group so far. First simulation results were presented in 2009 [48, 49], and a six-piston and two outlet system has been implemented and measured [50].

2.6. Combining Different Approaches

Both the parallel connection and switching technology has their own strengths and challenges. The new approach is to combine these in order to gain benefits of both and reduce challenges. Huova and Plöckinger [51] replaced the smallest bits of a DFCU with a fast switching valve and achieved very good velocity resolution of a cylinder drive. Pressure pulsation was also very small when compared to pure switching approach.

2.7. Valve Research

All digital fluid power solutions use on/off valves. The name switching valve is also used in the context of switching systems. Valve research can be divided into measurements and improvements of commercial valves, new valve prototypes, and control electronics for valves.

The combination of the control electronics and valve determines the performance and thus proper control electronics is very important. Unfortunately, only few commercial control electronics are available [52, 53]. The features must include overvoltage for rapid current rise, low hold voltage for reducing energy consumption, and negative voltage for fast current drop. The speed up factor of three is typical when proper control electronics is used. The approach of the author's group has been to use commercial

valves as far as possible together with own control electronics [54]. Typical response time is 8-12 ms for directly operated cartridge valves and CETOP 3 spool valves, which is enough in most cases for the parallel connected valve systems.

The switching technology calls for fast and continuous switching of valves. Typical switching frequency is 50 Hz and the implementation of 10 % duty cycle means 2 ms open time for the valve. Thus, response time requirement for valve is 1-2 ms and such valves have been available for tiny flow rates only. This is why the Prof. Sheidl's research group and Linz Center on Mechatronics have developed several different fast switching valve prototypes. The current spool type valve has 2 ms response time, 10 l/min flow rate at 0.5 MPa pressure differential and integrated control electronics [52]. Fatigue tests have been made up to 100 million cycles.

2.8. Number of Publications in the 2000s

Figure 9 shows the number of digital fluid power publications in the selected fluid power conferences. The numbers are estimates because it is sometimes difficult to determine if the paper is about digital fluid power or not. The poster sessions are excluded. The trend is clear and practically every conference has nowadays own session(s) for digital fluid power.

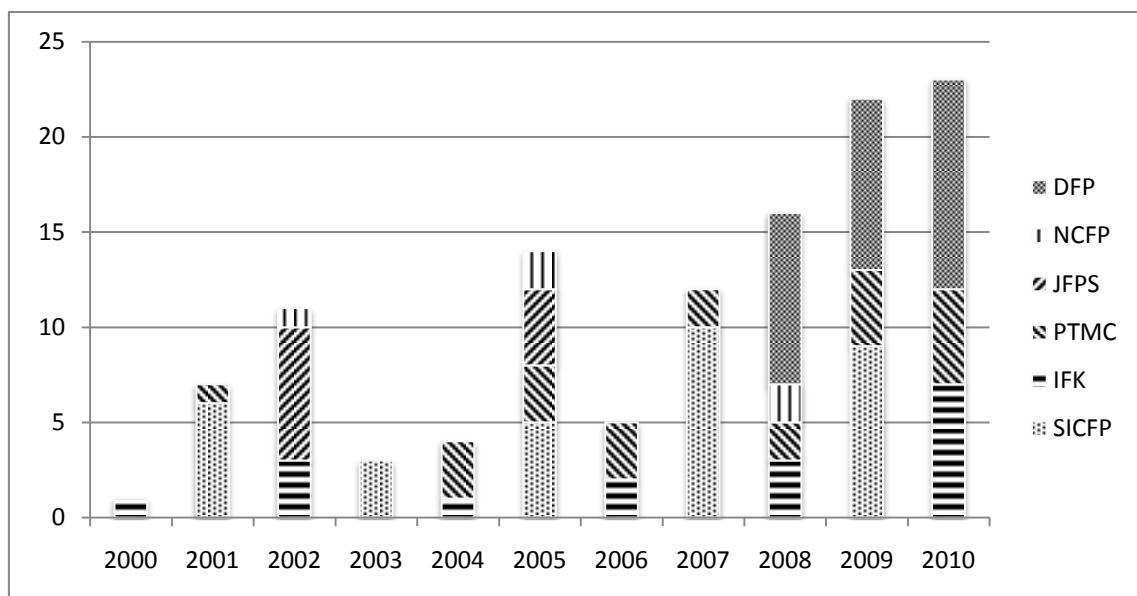


Figure 9. The number of publications related to digital fluid power in some conferences and workshops.

SICFP = Scandinavian International Conference on Fluid Power (biennial, Tampere/Linköping)

IFK = International Fluid Power Conference (biennial, Aachen/Dresden)

PTMC = Power Transmission and Motion Control (annual, Bath)

JFPS = JFPS International Symposium on Fluid Power (triennial, Japan)

NCFP = National Conference on Fluid Power (triennial, USA)

DFP = Workshop on Digital Fluid Power (annual, Tampere/Linz).

3. CHARACTERISTICS OF DIGITAL FLUID POWER SYSTEMS

3.1. Introduction

The characteristics of different branches of the digital fluid power have been discussed deeply in many publications and this chapter shortly presents the main characteristics only. Directional valve function is used as an example although the discussion applies for digital pumps of Fig. 3 also. Multi-chamber cylinders and digital hydraulic power management system are somehow unique solutions and they are discussed separately.

For the deeper understanding of characteristics of digital fluid power, following publications and their references are recommended: Switching converters and components of switching hydraulics [55]; Characteristics of parallel connected valve systems [56]; Model based control of parallel connected valve systems [28]; Fault tolerance of parallel connected valve systems [30, 31]; Transient uncertainty and pressure peaks of parallel connected valve systems [29]; Energy efficiency of different digital hydraulic solutions [57]; Reduction of power losses by parallel connected valves [32, 33]; Digital pump-motors [41]; Digital hydraulic power management system [48, 49, 58]; Linear transformer of Fig. 7 [2].

The complete list of publications of the Linz research group can be found in <http://imh.jku.at/publications/index.en.php>, and publications of the author's group by search from the TUT library database (<http://www.tut.fi/library/dlib/bibliography.html>).

3.2. Why Digital Fluid Power?

Strong research effort and interest on digital fluid power means that it probably has some benefits when compared to traditional systems. Here is a short list of the claims found in the publications:

- 1) Robust, simple and reliable components
- 2) Better performance because of faster valves
- 3) Higher degree of flexibility and programmability. However, the same can be achieved by new analogue solutions also.
- 4) Unification of hydraulic components. Control software determines the characteristics instead of valve spool, for example. This can also be achieved by distributed analogue valve systems.
- 5) Higher efficiency in pump, motor and transformer functions.
- 6) Completely new solutions are possible, such as switching converters and DHPMS.

Of course, challenges are also remarked on:

- 1) Noise and pressure pulsation
- 2) Durability and life time with switching technology
- 3) Physical size and price with parallel connection technology
- 4) Complicated and non-conventional control

3.3. Characteristics of Parallel Connected Systems

3.3.1. Quantized Output

A fundamental characteristic of the parallel connected systems is that the output is quantized. If the system consist of N parallel connected components each having two states, the total number of state combinations is 2^N . Each of the state combinations may give different output (e.g. flow rate) and thus the maximum number of output values is equal to the number of the state combinations. The actual number of output values depends on the coding method, or the relative size of components. The smallest number of output values is achieved by using components with the same size, and the number of output values is $N+1$. This method is known as Pulse Number Modulation (PNM) coding). The other extreme is binary coding in which each state combination gives different output value.

An important feature of the parallel connected systems is that no switching is needed in order to maintain any of the discrete output values. Once the state combination is selected and the control valves have achieved their positions, the output remains constant without any further actions. Some valve switchings are needed only when the state combination changes.

The digital flow control unit of Fig. 1 (b) is the most famous example of the parallel connected system. Each valve has two states and the output is the total flow area of the valves. Under constant pressure difference over the DFCU, the flow rate and actuator velocity are directly related to the flow area. Figure 10 shows the relative output for as a function of valves for different number of valves and for binary and PNM coding. The resolution improves exponentially when binary coding is used, which allows in theory very accurate control with relatively few valves. The limiting factor is the minimum orifice size allowed for the smallest valve. The PNM system has poor resolution but some interesting benefits, which are discussed later.

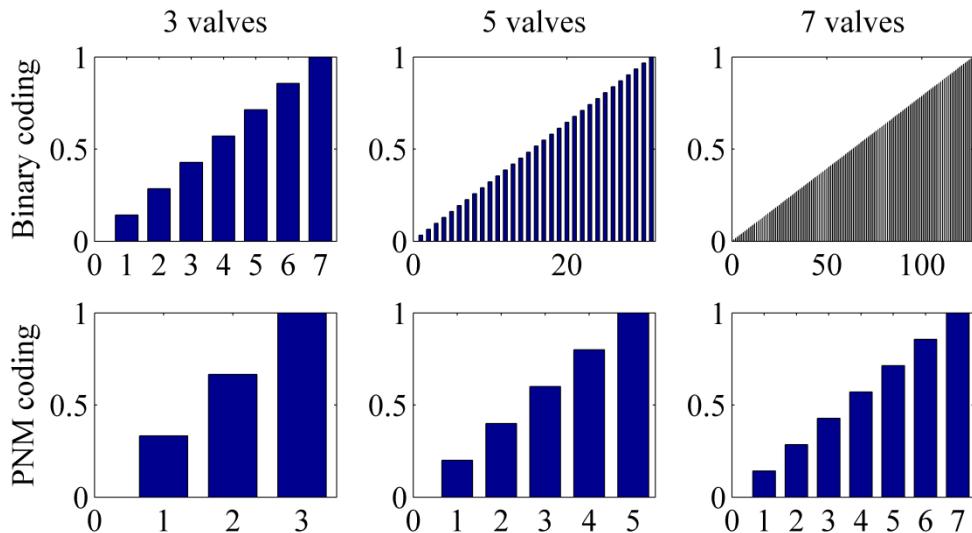
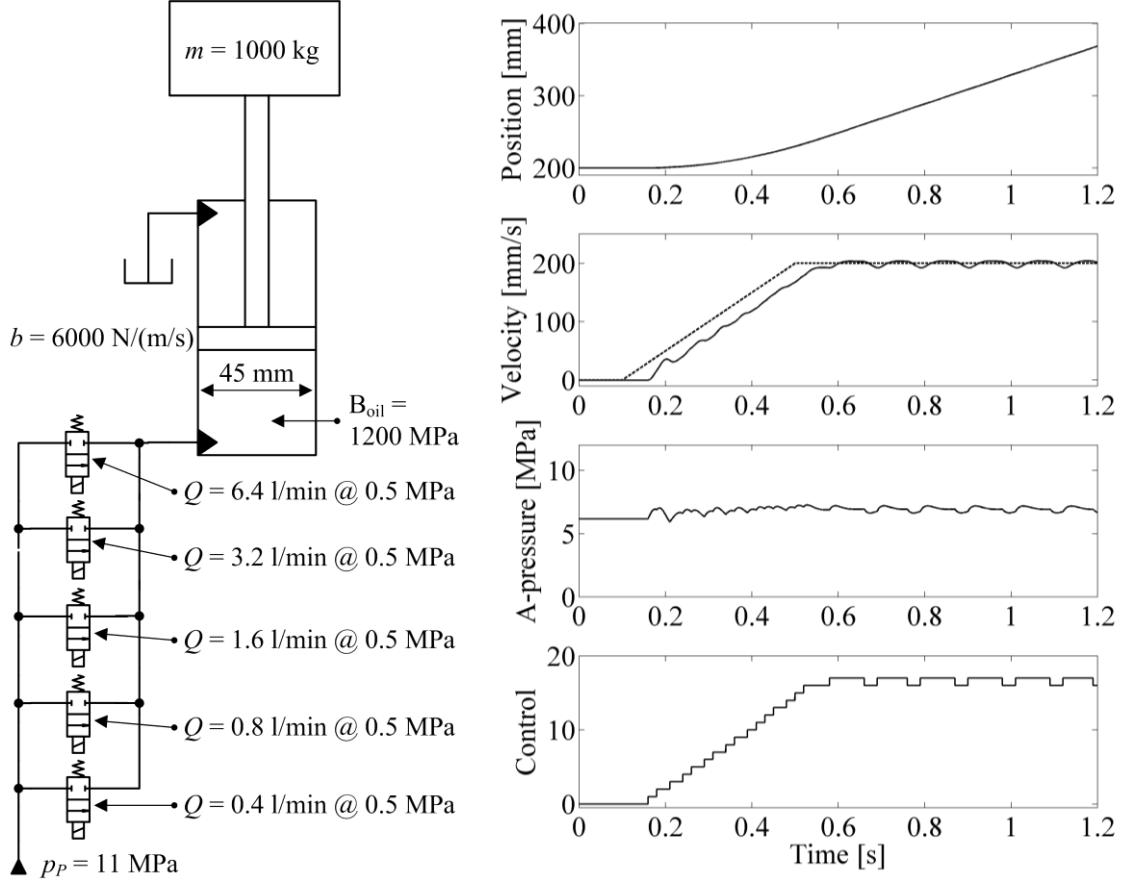


Figure 10. Relative DFCU output with binary and PNM coding for 3, 5 and 7 valves.

DFCU is almost like quantized version of the traditional two-way proportional valve. The purpose is to control flow area and control principle is throttling control. The output

controlled is the flow rate of the DFCU and thus the piston velocity. Discrete-valued output means that velocity cannot be adjusted exactly on the target value. This results in velocity behaviour shown in Figure 11 in the closed loop control. Target velocity cannot be achieved exactly and the controller switches now and then between two states.



*Figure 11. Simulation result of a single acting cylinder driven by a 5-bit DFCU and I-type velocity controller (gain = 100, sampling time = 10 ms).
Hydraulic losses are 1.09 kJ.*

3.3.2. Fast and Amplitude-Independent Response Time

The components of the parallel connected systems work independently on each other. This means that arbitrary changes in the output are possible. It is possible to switch a DFCU directly from 0 to 100 % opening; it simply means that all parallel connected valves are opened simultaneously. The response time depends only on the response time of individual components and not the amplitude at all. The state of the art valves have switching time about 2 ms, which means 2 ms full amplitude response time for DFCU or digital hydraulic four way valve. The fast response time is important especially in the energy efficient cylinder control in which the switching-on-the-fly between inflow-outflow and differential control mode is needed [32]. Fast and amplitude-independent response time is true also for parallel connected pump of Fig. 3 (b) and DHPMS of fig. 8 (b). The full amplitude response time of 3 ms is only a dream for traditional pump technology but is not a challenge for the digital parallel connection approach.

3.3.3. Fault Tolerance

Fault tolerance is inherent and unique feature of parallel connected systems. In the most cases, the system can run with slightly reduced performance even if one of components does not work. This requires fault detection and compensation by software. The fault tolerance depends strongly on the coding method. The binary coding is the most vulnerable while PNM coded system with sufficiently many components can work almost perfectly even if the fault is not detected. Figure 12 depicts the fault tolerance of a 5-bit binary coded DFCU and 31-bit PNM coded DFCU against “valve does not open” type fault. The “valve does not close” is more difficult situation but can also be compensated up to some degree.

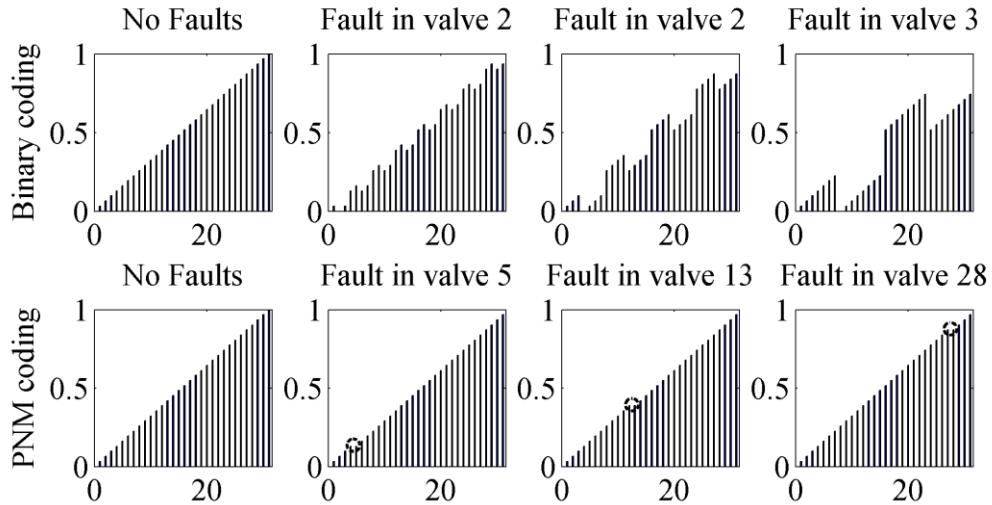


Figure 12. The effect of some valve faults on the 5-bit binary coded DFCU (first row) and 31-bit PNM coded DFCU (second row).

3.3.4. Transient Uncertainty

The transient uncertainty is the most important source of pressure peaks and noise in the parallel connected systems. The transition from a state combination to another may require simultaneous switching of some components off and others on. If the timing of these switchings is not exact, the output is unpredictable for a moment. This uncertainty region starts when the first component starts to operate and finishes when the last component has been settled. The worst state transition is when the biggest component is switched on and the others are switched off or vice versa. The duration of the uncertainty region can be reduced by using components with small uncertainty in the switching time, and the coding method has also a strong effect on the size of the transient uncertainty. Figure 13 shows the transient uncertainty for a binary coded and PNM coded DFCU. The problem is the biggest in the binary coding while the phenomenon does not exist at all in the PNM coded system.

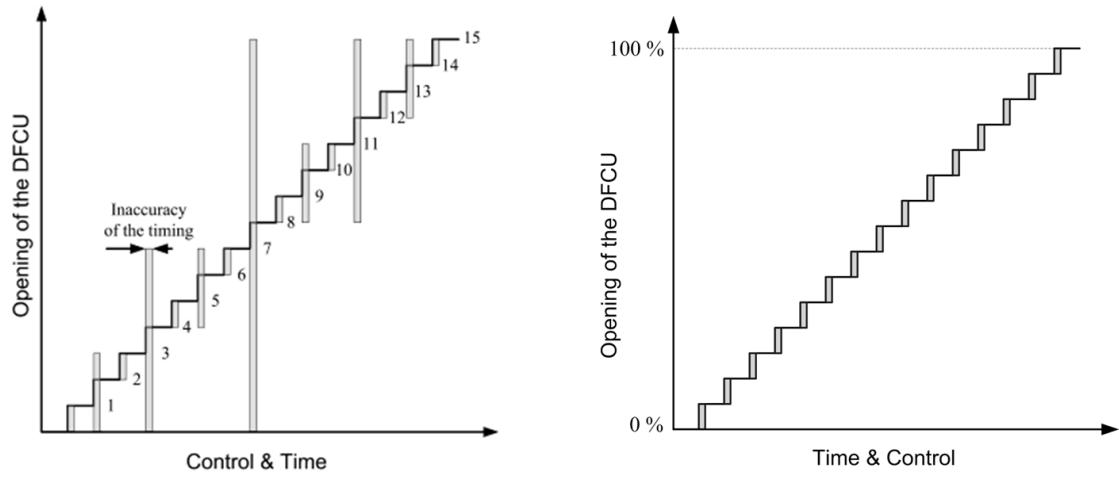


Figure 13. Transient uncertainty of the 4-bit binary coded (left) and 15-bit PNM coded DFCU when the output increases linearly. Infinitely fast valves with uncertain delay are assumed.

3.3.5. Large Number of Components, Harmonization, Mass Production

The implementation of a good four-way valve functionality requires 4×5 valves when binary coding is used and about 4×30 valves when PNM coding is used. Thus the number of components seems to be large when compared to the traditional solutions, but it is important to consider whole system. A mobile proportional valve consists of pressure compensator, main spool, two pilot valves, pilot pressure circuitry, and a number of springs and damping orifices. It also requires counterbalance valve in order to work properly with overrunning loads. The digital solution has 20-120 identical zero-leak valves with simple control electronics and the control code implements all the functionality.

An important benefit of the digital approach is that only some different components are needed. Almost all valve applications could be implemented if there were 2 ms valves available for flow rates 2, 16 and 128 l/min (for example), because the other sizes can be implemented by adding the orifice disc after the valve. This means large number of similar components and mass production can be applied, which reduces the price per valve.

3.4. Switching Systems

3.4.1. Dynamic behaviour

Consider a switching control system of Fig. 14. The system is similar to the system of Fig. 11 but the DFCU is replaced with a single on/off valve and an ideal check valve. When the valve is open, pressure rises quickly close to the supply pressure and the load mass accelerates. When the valve closes, pressure starts to decrease. The mean velocity is achieved by fast switching and adjustment of the ratio between on and off time of the valve. This results in velocity and position behaviour shown in Fig. 14. Velocity ripple is significant and the main reason for too small inertia of the system for the control

approach. Thus, some kind of damping device should be used in this system. Hydraulic losses are now 0.70 kJ and thus significantly smaller than 1.09 kJ in the resistance control system of Fig. 11. The reason is that the system utilizes suction from the pressurized tank line.

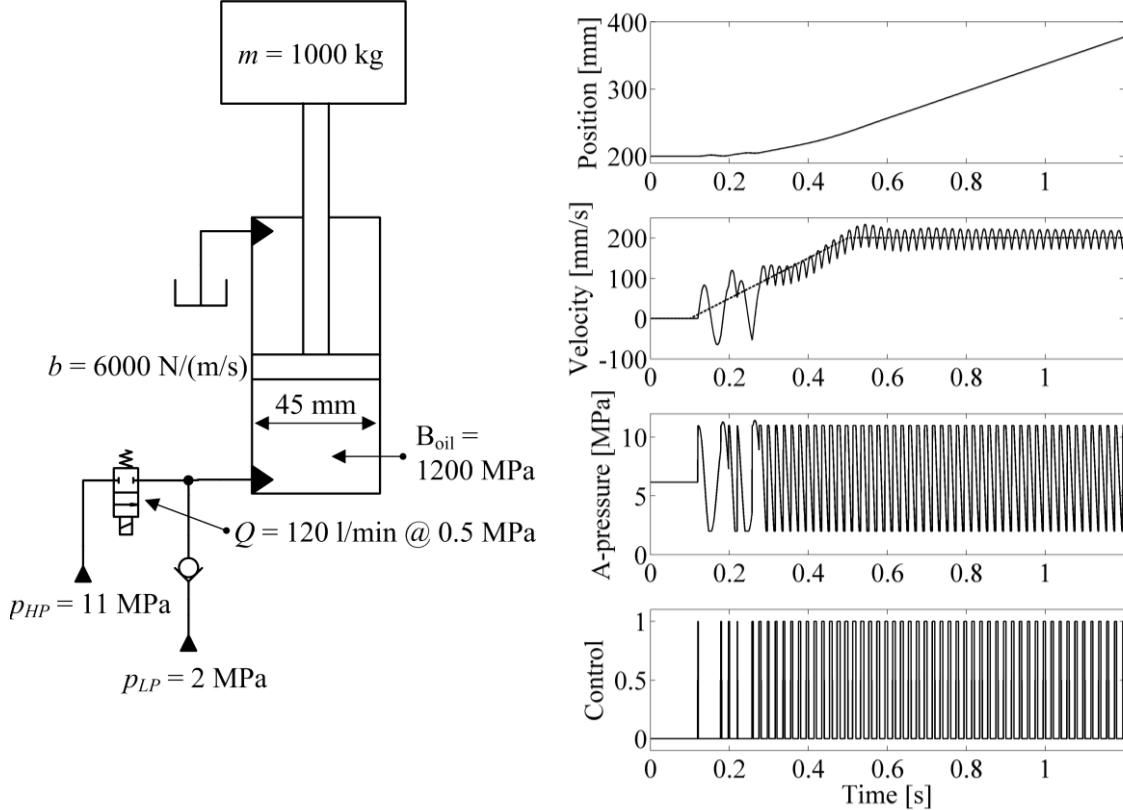


Figure 14. A simple switching control system and its simulated response. I-type velocity controller is used (gain = 100, sampling time = 0.1 ms). The PWM frequency is 50 Hz and minimum duty is 5 %. Hydraulic losses are 0.70 kJ.

3.4.2. Lower Number of Components

Switching systems need fewer valves than parallel connected systems because single valve is used instead of DFCU. However, energy efficient implementations require additional check valves, pipes, and hydraulic capacitances for good control characteristics.

3.4.3. Lossless Control

The most important benefit of switching control is that it is lossless, at least in theory. The same principles are used as in electric switching power supplies and inverters. The efficiency of these electric systems is very good and output ripple is also at acceptable level. The fundamental difference to electric systems is that significant parasitic capacitances exist, which causes that the efficiency of hydraulic switching systems is not so good. Measured efficiencies of properly designed switching converter are 70-85 % [19].

3.4.4. Continuous Switching, Wear and Noise

The fundamental characteristic of switching systems is that only few output values are available and the mean output is adjusted by continuous switching. This results from the fact that only some binary components are used and the maximum number of output values is equal to 2^N . This results in jerky movement as seen in Fig. 14. The amplitude of the velocity ripple can be reduced by increasing switching frequency, increasing the system inertia and/or introducing damping elements.

Continuous switching causes noise, which can be reduced by the careful design. Another implication is huge number of valve switchings. Typical switching frequency is 50 Hz, which implies 180000 switchings per hour, 130 million switchings per month and 1.6 billion cycles per year. Thus, the technology is not yet suitable for systems where continuous movement is needed.

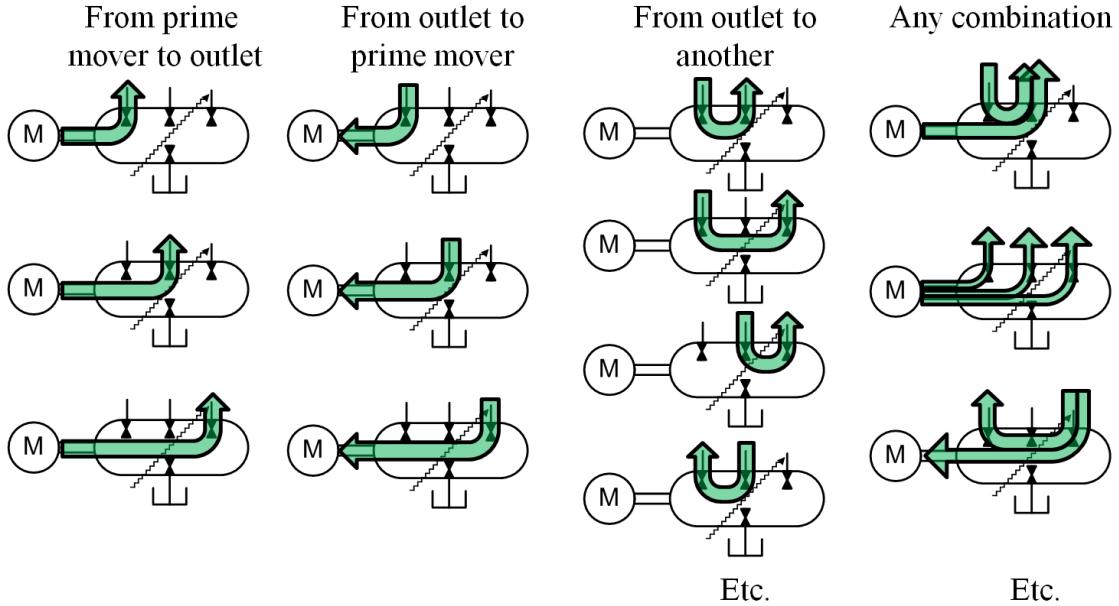
3.5. Multi-Chamber Cylinders

Consider the multi-chamber cylinder of Fig. 6 (c). If the control valves are large on/off valves – as in the figure – the system can generate 16 different forces. Sufficient inertia is needed for proper controllability and the system can be seen as secondary controlled cylinder without any losses. In practice, small compressibility and flow losses occur, but according to the author's knowledge, this approach is the most energy efficient way to control hydraulic cylinder from the constant pressure lines. The weak point is that continuous switching between control modes is required in order to obtain quasi-steady velocity. The situation is not so demanding as in the switching systems because there are much more force values available.

If the on/off valves are replaced by directional valves, such as two-way proportional valves or DFCUs, the result is the extended version of the normal cylinder plus distributed valve system with pressurized tank. Losses are much smaller than in traditional systems because the pressure losses can be optimized by selecting the correct control mode on the fly [45]. This approach combines good performance of the valve control and small losses, but the control code – especially the mode switching logic – becomes very complicated.

3.6. Digital Hydraulic Power Management System

The general functionality of the Digital Hydraulic Power Management System (DHPMS) is interesting: One machine having number of independent outlets each behaving like digital pump-motor. The pressures and flow directions at outlets are arbitrary and have practically no effect on losses. This means for example that hydraulic power from the load lowering can be recovered to the accumulator even if accumulator pressure is higher than load pressure. Thus, the whole energy storing capacity of the accumulator can be utilized. Figure 10 presents some possible power flows of the DHPSM with three outlets.



*Figure 15. Some possible power flow of the DHPMS.
Simplified drawing symbol is used.*

There are two possible ways to implement DHPMS as shown in Fig. 8. Both have similar controllability: each outlet has only certain smooth flow values and the output is thus quantized. The number of output values depends on the number of pistons or fixed displacement units, and also on the coding method in the case of the DHPMS based on fixed displacement units. Possible flow rates are symmetric around zero and relative flow rates could be 0, $\pm 20\%$, $\pm 40\%$, $\pm 60\%$, $\pm 80\%$ and $\pm 100\%$ of maximum flow. The controllability is explained in detail in [58].

The piston type DHPMS is closer to switching systems because continuous valve switching is needed. Thus, the durability and energy consumption of valves are challenges. The control bandwidth is also limited because the controller must wait until the next piston is at the correct phase in order to change the output value. On the other hand, this kind of machine can have very good efficiency (over 95 %) at wide operation range [41]. The reasons are the small idling losses of pistons and the fact that the energy stored in the oil compressibility can be recovered.

The DHPMS based on fixed displacement units is the true parallel connected system and no valve switchings are needed in order to maintain any flow combination of the outlets. Response is fast because it is equal to the response time of the control valves. The efficiency is unclear as no research results are available.

4. DEVELOPMENT TRENDS

The most important development trend of the digital fluid power seems to be new energy efficient solutions. The main approaches are:

- 1) Digital pump-motors. The Artemis Intelligent Power Ltd. is a pioneer in this area. The main application area is hydrostatic transmission.
- 2) Transformers. Two research lines are switching converters (Linz) and linear transformers (Digital Hydraulics LLC).

- 3) Multi-Chamber Cylinders. The research started at the Tampere University of Technology and has been continued by Norrhydro Ltd.
- 4) DHPMS. The research is in early phase and has been made in the Tampere University of Technology only.

All these have very good theoretical efficiency but lot of experimental validation is needed. Analogue versions exist only for pump-motor and transformers.

Another trend is valve development. Several good prototypes have been demonstrated by the research institutes but commercial solutions are few. One possible approach is the strong increase of the number of valves because it yields perfect controllability and fault tolerance. The main challenge of this approach is the price of the components.

Recent approach is to combine different approaches. The combination of traditional DFCU with few bits and small switching valve(s) is a promising approach, for example.

5. CONCLUSIONS

This paper shows that digital fluid power is broad research field and several research institutes and companies contribute the research. The technology offers several new ways to implement highly efficient hydraulic systems. Interesting feature is that systems are not complicated; they may have several components but they all are the same type. Digital fluid power means big harmonization of hydraulics because all functions can be implemented by simple on/off valves and fixed displacement units. The side effect is that control code becomes complicated because it implements all the functionality.

The biggest obstacle of the application of digital fluid power is the lack of commercial valves. There is an urgent need for good valves, valve packages and control electronics all integrated in a nice package. The implementation of all functionality required, proper user interfaces and compatibility with traditional systems need to be solved as well.

One surprising fact is that digital principles are not studied lot in pneumatics where it should offer similar advantages. Availability of components is much better and noise and pressure peaks problems should be much smaller.

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