Digital Hydraulics – Towards Perfect Valve Technology*

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Abstract: Digital Hydraulics is a recently developed alternative for traditional control with servo or proportional valves. The key principle is to use parallel-connected two-way on/off valves together with intelligent control. This paper analyses characteristics of different digital valve systems. It is shown that valve system having equally sized valves is in many senses optimal solution. The feasibility and achievable performance of this approach is discussed. It is shown that the technology has potential for ten times faster response than existing valves and good fault tolerance. Miniaturization is shown to be essential method in implementation of this kind of valve systems.

Keywords: Digital hydraulics, on/off control, miniaturization,

1 Introduction

1.1 Background

Great majority of hydraulic systems are based on analogue control components, such as proportional valves and variable displacement pumps. Benefits of analogue systems are e.g. simple and smooth control. On the other hand, analogue components may be expensive and sensitive to contamination, temperature, vibration etc. Analogue systems have been superseded by digital systems in many fields. Some examples are cameras, displays, computers and music. Digital technology is not limited to electronics but it can be applied in any field of technology. Old examples are DNA code, smoke signs and Morse code, and modern examples are ABS brakes and fuel injection of modern cars [1, 2].

By definition, digital systems utilize discrete value components. Some general principles of digital technology are plurality of similar components (e.g. pixels), AD and DA conversion and intelligent control. Important benefits of digital technology are robustness, repeatability and fault tolerance. The most common solution is to use binary components and it is easy to determine if the signal is ON or OFF. This makes digital systems repeatable and insensitive to noise. Plurality of similar components makes digital systems redundant. For example, failure in single pixel of digital camera causes only a negligible reduction in performance. 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.

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Challenges of digital technology are large number of components and/or risk for jerky control. 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. Also, increased performance, programmability and flexibility (e.g. MP3 player compared to LP disk) have helped to tolerate increased price.

1.2 Classification of Digital Principles in Hydraulics

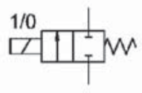
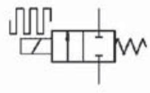
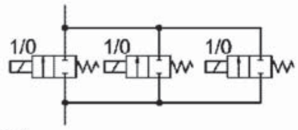
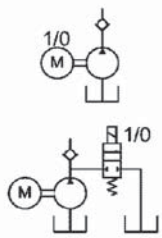
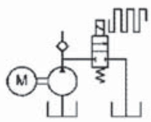
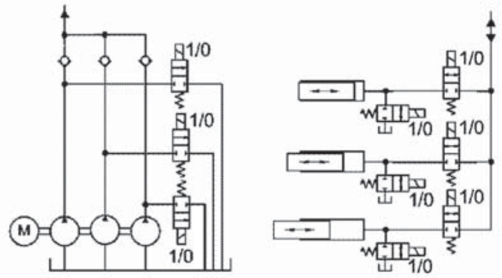
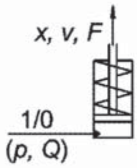
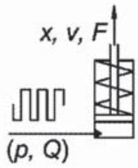
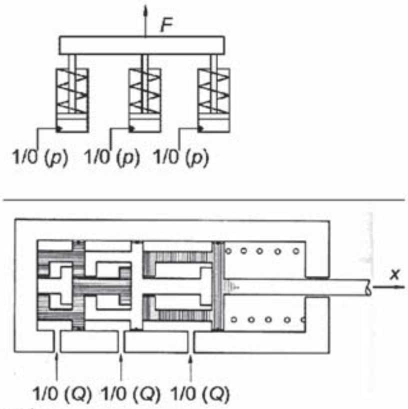
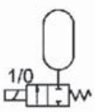
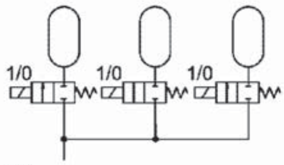
Digital technologies in hydraulic systems can be divided into three major classes as shown in *Table 1*. The simplest one is traditional on/off technology, in which the output of the system has only two discrete values, such as motor/pump rotating or stopped, cylinder moving or stopped, pressure high or low. Hydraulic cylinder controlled to one or another end can also be included in this class. The second major class is switching techniques, which mimic principles of electric switching systems. The most popular variant is pulse width modulated (PWM) on/off valve. Switching techniques rely on extremely fast switching and the main benefit is simple hydraulic hardware. The purpose is to produce analogue-like output via high-frequency modulation and filtering. The third class is the utilization of parallel-connected components. The systems are truly digital because the output has only discrete values. Output level is defined as a sum of outputs of ON components. Essential difference to switching techniques is that no switching is needed to maintain any of discrete output values. This technology is called here Digital Hydraulics.

Switching techniques have been under active research already for decades. Scheidl and Manhartsgruber [5] give a good overview of switching techniques and this material is not repeated here. Some discussion can also

cars [1, 2]. Switching controlled pump (*Table 1* (f)) has been studied in [7].

Parallel connected on/off valve series of Table 1 (h) is an old invention [8, 9], but it has been applied quite

Table 1. *Classification of digital principles in hydraulic circuits and some example circuits. (*Lower picture of (j) from [3])*

	On/Off Technology	**Switching Technologies**	**Digital Hydraulics**
Valves	 (a)	 (e)	 (h)
Pumps	 (b)	 (f)	 (i)
Cylinders	 (c)	 (g)	 (j)*
Capacitances	 (d)		 (k)

1.3 State of the Art

Basic on/off technology is not studied much nowadays. This is probably because the technology is considered as old-fashioned. However, the on/off control is the best solution for cases in which its control characteristics can be tolerated, and the approach is very popular in pneumatic systems. A short survey on on/off control is given in [4].

be found in [4]. The biggest challenge of switching techniques is the development of extremely fast, reliable and energy efficient on/off valve. Traditional valve technology seems not to be able to satisfy these requirements, but the resonance valve concept [6] seems promising approach. The most important commercial applications of switching techniques are ABS brakes and fuel injection systems of modern

seldom in 20th century [10–12]. The development of valves and control techniques has resulted in extensive research and development of this technology since 2000 [13–21]. The results of this research can be summarized as:

- Digital hydraulic valve systems can significantly save energy similarly as analogue distributed valve systems [13]

- The valve system is fault tolerant and failure in single valve does not prevent the use of actuator [14, 15]
- Performance is comparable or better to analogue counterparts [13, 16, 17]
- Rather complicated controllers are needed [13, 18–20]
- Proper design is needed in order to avoid pressure peaks [21]

Parallel connected pumps (Table 1 (i), left) are routinely used in many applications. Another way to implement digital pump is so called digital displacement technology shown in right side of Table 1 (i) [22, 23]. The idea is to actively control operation of each piston of the pump by on/off valves. Each piston can be independently in idle mode, pump mode or motor mode. This results in better efficiency and controllability but for some reason, the approach is not widely adopted.

1.4 Definition of Terms Used Together with Digital Hydraulics

Most of this paper deals with digital valve systems, such as Table 1 (h). The terminology is not well-established and following definitions are used in this paper (see also *Figure 1*):

DFCU (Digital Flow Control Unit) – Group of two-way two-position on/off valves connected in parallel.

Digital valve system – Configuration of several DFCUs. For example, four-way digital valve system.

Digital Hydraulics – Hydraulic systems, which utilizes parallel-connected binary components. Output has only certain discrete values. See Table 1.

Coding or **Coding scheme** – 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, … , 2^{N-1}), Fibonacci coding (1, 1, 2, 3, 5, 8, … , $P_{N-2}+P_{N-1}$) and Pulse Number Modulation (PNM) coding (1, 1, 1, 1, … , 1).

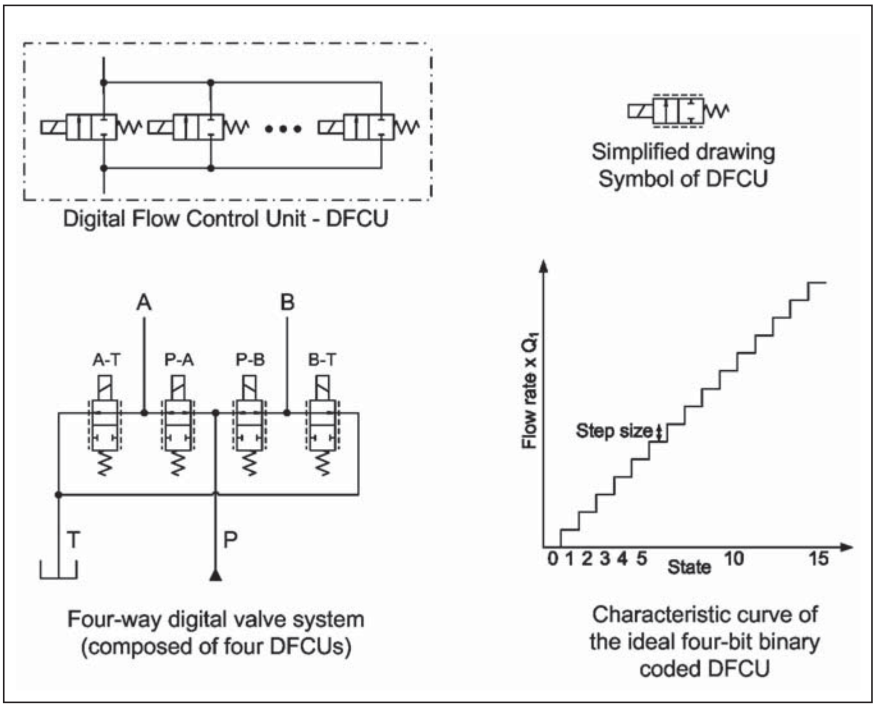


Figure 1. *Some definitions of digital valve systems*

N-bit DFCU – DFCU with *N* parallel connected valves. For example, four-bit DFCU, seven-bit binary-coded DFCU.

PNM-coding (PNM = Pulse Number Modulation) – Coding scheme in which all valves have the same flow capacity.

PNM control – Control method in which output is changed either by opening or closing valves. This means that simultaneous opening and closing of valves never happen in DFCU.

State of DFCU – Binary vector with *N* elements or integer number between 0 and 2^N–1. State determines open and closed valves of DFCU. For example, state [1 0 1 0] or 5 means that the first and third valves are open and the second and fourth valves are closed.

Step size – Change in output of DFCU when the state is changed by one. Ideally, equals to flow rate of the smallest valve of DFCU.

1.5 Objectives of the Paper

The main objective is to find out, which kind of performance is possible with digital valve technologies, such as shown in Table 1 (e) and (h). At first, the availability and characteristics of existing on/off valves is introduced. Then requirements set by different digital valve technologies are analyzed and performance of some valve systems is presented.

2 Characteristics of On/Off Valves

2.1 Commercial Valves

Commercial on/off valves are widely used in simple tasks, such as switching hydraulic motor on or off. The response time is not critical in these applications and slow response is many times advantageous in order to reduce pressure peaks. These facts have caused that commercial valves have only moderate performance. Fortunately, characteristics can be significantly improved with proper control electronics and slight modifications [24]. *Table 2* presents measured characteristics of some commercial on/off valves. Problem with directly operated valves is that they cannot tolerate high pressure differentials. Pilot operated valves do not have this problem but they have longer and more varying delay.

Table 2. *Measured characteristics of some commercial on/off valves [16, 24]*

Valve type	Direct operated spool (NS4)	Direct operated spool (NS6)	Direct operated seat valve with dynamic seal (Screw-in cartridge)	Pilot operated seat valve (Screw-in cartridge)
Valve manufacturer & type	Bosch Rexroth 4WE420/ EG24N9K4	Moog WE43P06… E03PC0BN	Hydac WS08W-01	Sterling Hydraulics GS0205
Control electronics & modifications	Opening and closing booster, structural modifications	Opening and closing booster, structural modifications	Opening and closing booster	Closing booster
Response time	8-10 ms	8-12 ms	5-8 ms	10-40 ms
Nominal flow Q_N @ 3.5 MPa	75 l/min	200 l/min	36 l/min	52 l/min
Max. pressure differential	3.5 MPa	6 MPa	3.5 MPa	21 MPa
Size excluding connectors	168×37×39 mm	208×45×48 mm	36.3×95 mm	34×40×91.5 mm

2.2 Special Valves and Valve Prototypes

Standard hydraulic on/off valves are not optimized to be used together with modern digital technologies. This is why many on/off valve prototypes have been developed [25–28]. Automotive industry utilizes also modern on/off valves in fuel injection, brakes and valvetrains [1, 2]. *Table 3* presents characteristics of some of these valves.

Table 3. *Characteristics of some special valves and valve prototypes*

Valve type	Direct operated bistable spool	Direct operated spool (NS10)	Direct operated bistable seat	Pilot operated seat
Valve manufacturer & type	Sturman Industries SI-1000 [2]	Linz Center of Mechatronics GmbH [25]	Tampere University of Technology [26]	Tokio Institute of Technology [27]
Response time	0.45 ms	2 ms	1.5-3.5 ms	1-2 ms
Nominal flow Q_N @ 3.5 MPa	32 l/min	120 l/min	10 l/min	~6 l/min
Max. pressure differential	n.a.	14 MPa	21 MPa	14 MPa
Size excluding connectors [mm]	Approx. 110×35×35*	Approx. 90×90×110*	31×28.2	Approx. 50×150*

*Partial or no data available. Size estimated from figure.

3 Characteristics of Digital Valve Systems

This chapter analyses characteristics of PWM controlled valve and different digital valve systems. Characteristics are analysed in terms of uncertainty in output, response time, flow capacity, number of valves and fault tolerance.

3.1 PWM Controlled Valve

The output uncertainty of PWM controlled valve can be defined as difference between target duty ratio and true duty. Uncertainty depends on both the switching time and flow uncertainty as shown in *Figure 2*. Uncertainty depends also on switching frequency. Relative error *e* caused by variation in valve delay can be expressed as:

$$e_\tau = \frac{(\tau_{max} - \tau_{min}) f}{Duty} \qquad (1)$$

where $_{max}$ and $_{min}$ are maximum and minimum delay, *f* is switching frequency and *Duty* is duty ratio. Equation 1 shows that error increases with frequency and decreases with duty. This means that relative error becomes very big at small duty. Situation is even worse in practice because valve opening is highly unpredictable at very short pulses [2].

Response time of PWM controlled valve depends on valve dynamics and switching frequency. Valve response time must be a small fraction of switching period for successful duty control. A rule of thumb is that switching frequency is at maximum ten percent of inverse of valve response time. The basic principle of classical PWM approach is to filter output such that ripple at switching frequency remains reasonable. This

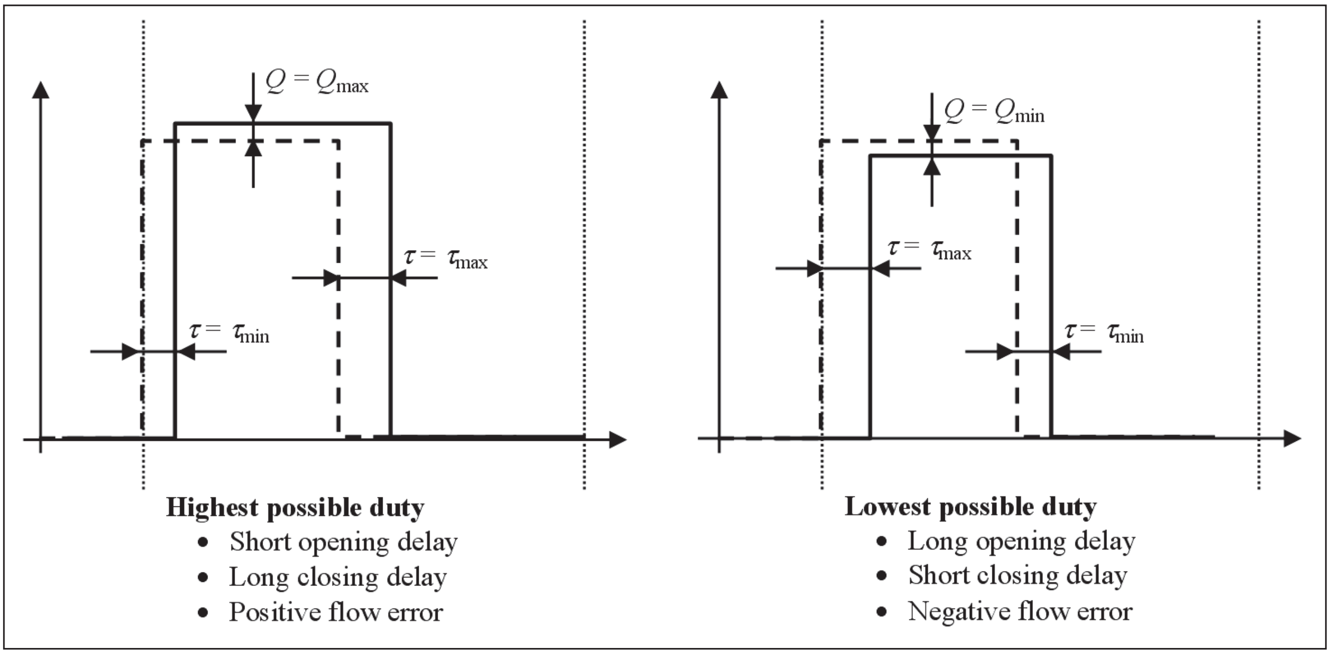


Figure 2. *Uncertainty of PWM duty cycle*

means that output bandwidth is a small fraction of switching frequency, usually less than ten percent. Thus, it can be concluded that response time of the output of the PWM valve is at least 100 times longer than response time of the valve.

Good feature of PWM controlled valve is that only one valve is needed. Side effects are that the valve must pass all the flow and that fault tolerance is poor. Durability requirements are also high because of continuous high frequency switching.

3.2 Binary-Coded DFCU

A binary-coded DFCU consists of *N* parallel connected on/off valves such that their flow capacities are [1 2 4 8 16 32 etc.]×Q_1 where Q_1 is the flow capacity of the smallest valve. The operation principle of the binary-coded DFCU is similar to DA converter and output has 2^N discrete values depending on which valves are open. The open valves are defined via *state vector*, which has *N* elements. For example, "three-bit" binary-coded DFCU has states [0 0 0], [1 0 0], [0 1 0], [1 1 0], [0 0 1], [1 0 1], [0 1 1] and [1 1 1]. Important difference to PWM approach is that no switching is needed in order to maintain any of these output values.

Steady-state output uncertainty depends on output uncertainty of open valves only. This means that relative uncertainty is constant, which allows exact control also at small openings. However, it is important to remember that DFCU can deliver only certain discrete flow rates and flow rate increases stepwise. Another steady-state uncertainty is step size uncertainty, which depends on state transition executed. Step size uncertainty is equal to sum of uncertainty of all valves, which change their state. For example, step size uncertainty of state transition [0 1 0]$\leftrightarrow$[1 1 0] is equal to output uncertainty of the smallest valve while step size uncertainty of transition [1 1 0]$\leftrightarrow$[0 0 1] is equal to sum of output uncertainty of all three valves. Assume for example that flow rate of the two smallest valves is two percent too big and flow rate of the third valve is two percent too small. The flow rate of state [1 1 0] is 3.06×Q_1 instead of 3×Q_1 and flow rate of state [0 0 1] is 3.92×Q_1 instead of 4×Q_1, which gives 14 percent too small step. Practical systems have five or six valves, which means that step size uncertainty can exceed step size for certain state transitions in the binary-coded DFCU. This phenomenon has been observed also in prac-

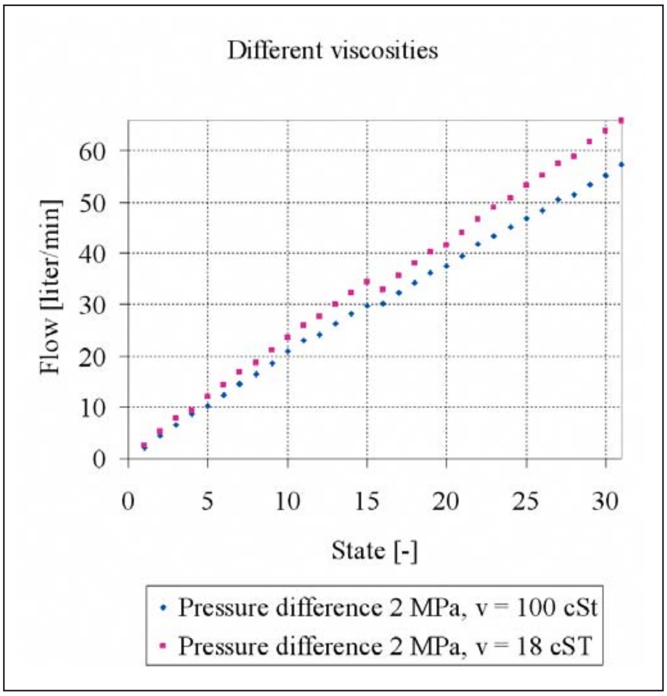


Figure 3. *The effect of viscosity on characteristics of a five-bit binary-coded DFCU. Note big change in step size of state transition 15 16. [29]*

tice; see [29] and *Figure 3*. Figure 3 shows also clearly that uncertainty caused by viscosity change is proportional to flow rate.

Response time of the binary-coded DFCU is equal to response time of individual valves and amplitude has no effect on response time. One special feature of the binary-coded DFCU is transient uncertainty. This is caused by the fact that certain state transitions require simultaneous opening and closing of valves. Variation in response times causes that some valve may close before another opens or vice versa. The result is short term uncertainty in the effective opening. This phenomenon has been studied in detail by Laamanen et al. [21]. *Figure 4* presents transient uncertainty for a four-bit binary-coded DFCU when its state increases linearly. Uncertainty is huge in state transition [1 1 1 0]↔[0 0 0 1]. The only ways to reduce uncertainty is to use valves with very small uncertainty in response time or to part with binary coding.

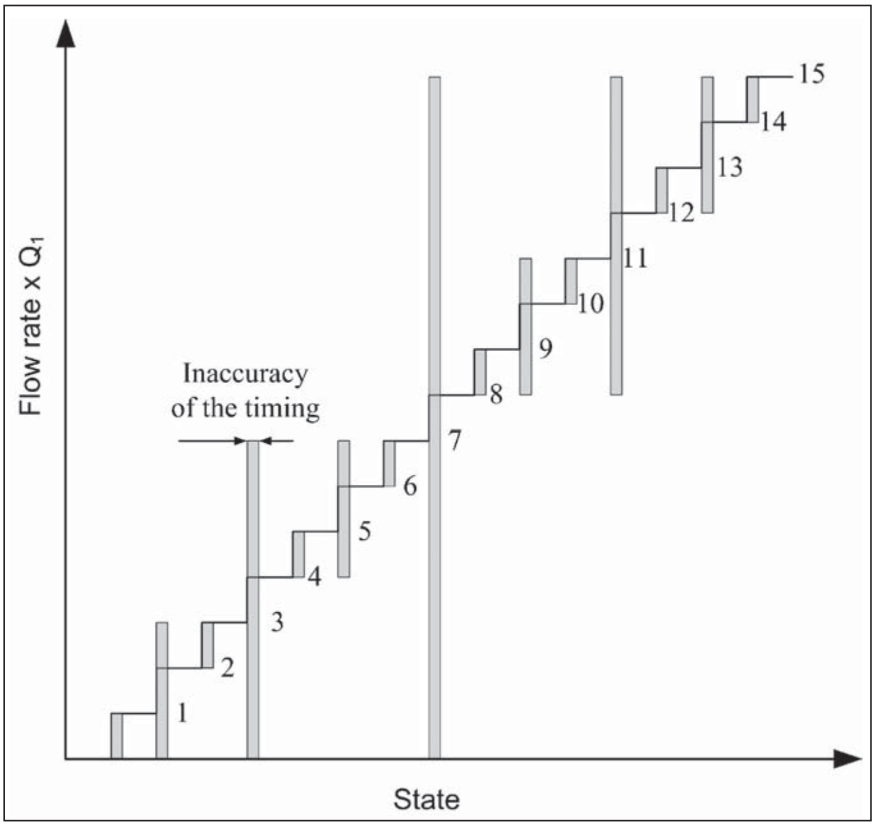


Figure 4. *Theoretical transient uncertainty of a four-bit binary-coded DFCU when state increases linearly*

The binary-coded DFCU requires five or six valves for good controllability. Flow capacity of the DFCU is approximately twice the flow capacity of the biggest valve. The flow capacity of the smallest valve is 1/16 (N = 5) or 1/32 (N = 6) of the flow capacity of the biggest valve. Thus, implementation of binary-coded DFCU requires different valve sizes or extensive choking of flow rate.

Fault tolerance of the binary-coded DFCU is good when compared to the PWM valve or any traditional analogue valve. Fault in any of the smaller valve has only a small effect on performance while bigger valves are more critical. It is important to detect faults in order to maintain controllability. *Figure 5* presents controllability in the case of five-bit DFCU. [14]

3.3 PNM-Coded DFCU

The binary-coded DFCU has the highest possible number of output levels but also some problems as described in the previous section. Pulse Number Modulation (PNM) coding is another extreme in which all valves have the same flow capacity. The number of output values is only N+1, which

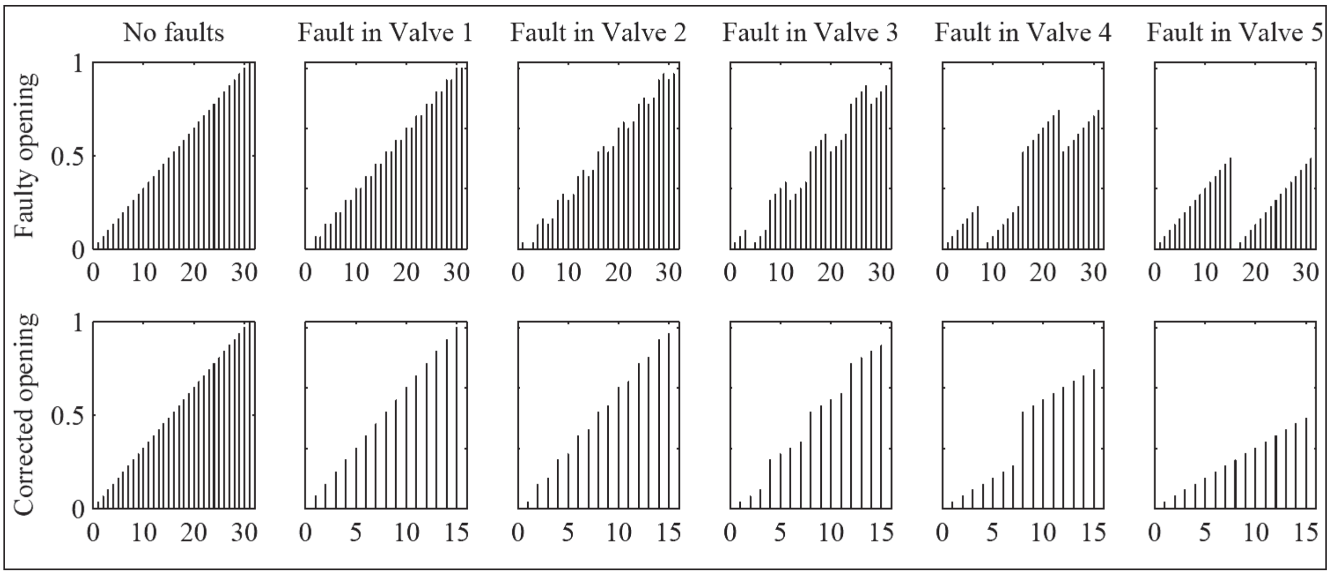


Figure 5. *Fault tolerance of five-bit binary-coded DFCU [14]*

means that a large number of valves is needed in order to achieve high resolution. Control principle is to open more valves when more flow is needed and close valves when less flow is needed, and there never exist simultaneous opening and closing of valves. The PNM-coded DFCU does not have problems of binary-coded DFCU, i.e.:

- Step size uncertainty is small, relative to step size and independent on state transition
- There is no transient uncertainty but opening is between initial and final opening during the state transition.
- There is no need for different valve sizes because all valves have the same flow capacity
- Fault tolerance is much better than in binary-coded DFCU. The only effect of failure in one valve is that flow rate does not increase in one state transition.

The only problem of the PNM-coded DFCU is the big number of valves. For example, 31 valves are needed in order to achieve the same resolution than with five-bit binary coding. On the other hand, only one type valves are needed and mass production may be used. The required flow rate per valve is small (1/*N*), which helps to achieve very fast response.

3.4 Mixed PNM-Binary Coding

Mixed PNM-binary coding tries to combine good characteristics binary and PNM-coding. Targets are set as follows:

- In normal conditions, control strategy must be PNM control, i.e. there are never simultaneous opening and closing of valves.
- In fault situation, binary-like control is allowed if transient uncertainty remains small.
- Number of valves must be reduced significantly from PNM-coded system
- Control resolution can be reduced at bigger openings

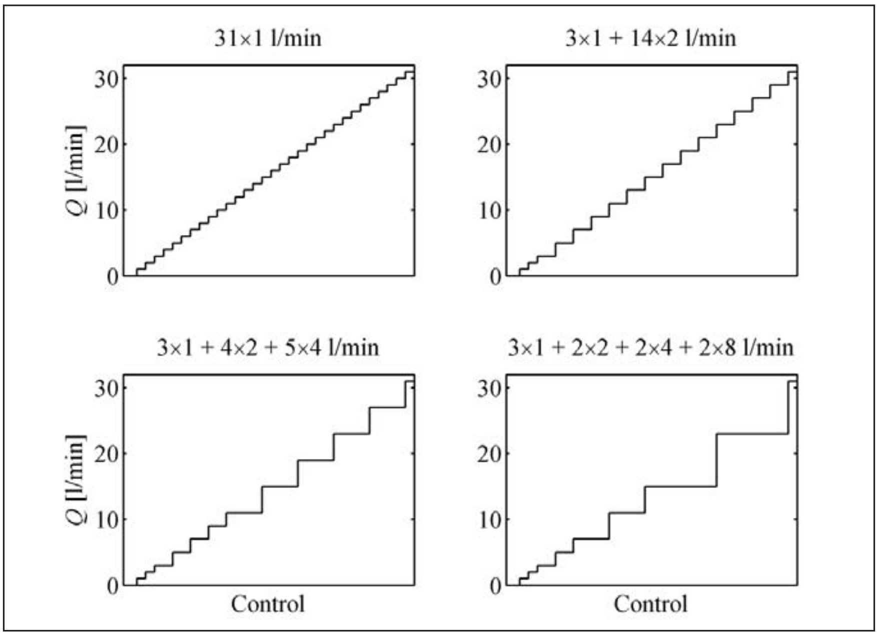


Figure 6. *Characteristic curves of pure PNM-coding and different mixed coding schemes when PNM control is used*

The last fact is based on analysis results of [18, 30], which shows that high resolution is needed only at small openings in four-way valve applications. Five-bit binary and 31-bit PNM-coded DFCUs are used as an example. For simplicity, it is assumed that step size is 1 l/min. Flow capacity of all valves is 1 l/min in pure PNM-coding. The number of valves can be almost halved if one 1 l/min valve is used together with fifteen 2 l/min valves. In order to improve fault tolerance and resolution, it could be better to have two or three 1 l/min valves. Several alternatives can be derived from this principle:

1) 3×1 l/min + 14×2 l/min (17 valves)
2) 3×1 l/min + 4×2 l/min + 5×4 l/min (12 valves)
3) 3×1 l/min + 2×2 l/min + 2×4 l/min + 2×8 l/min (9 valves)

Figure 6 depicts flow curves when PNM control is used. Note that all alternatives can deliver all 31 flow rates if binary like control is allowed.

3.5 Summary

Table 4 summarizes characteristics of digital valve systems together

Table 4. *Summary of characteristics of digital valve systems studied*

	PWM controlled valve	Binary- Coded DFCU	PNM-Coded DFCU	Mixed- Coded DFCU
Number of valves	Small	Moderate	Very large	Large
Steady-state uncertainty	Large	Small	Small	Small
Step size uncertainty	n/a	Big	Small	Small
Transient uncertainty	n/a	Big	Small	Small
Dynamic performance	Poor	Good	Best	Very good
Fault tolerance	None	Good	Best	Very good
Requirements for valves	- High flow - Extremely fast - Extreme durability - Exact timing	- High flow - Exact timing - Small size	- Small size	-Small size

with valve requirements. PWM Valve requires big, fast and durable valve as well as small uncertainty in switching time. Binary-coded DFCU requires also relatively large valve (the biggest valve) and exact timing. Response time itself is not critical but uncertainty in response time must be small in order to reduce transient uncertainty. PNM-coded DFCU has the best characteristics but the cost is strongly increased number of valves.

4 Miniaturization and PNM – Towards Perfect Valve

4.1 Definition of Perfect Valve

Well known design rule is to strive for impossible in order to obtain best possible solution. This kind of impossible "perfect valve" could be defined as follows:
Infinite bandwidth, no oscillations or overshoot.

- No uncertainty, perfect repeatability
- Unlimited durability
- Characteristics independent on fluid, temperature, pressure, wear etc.
- Fully programmable characteristics for optimal fit to any system
- Low costs and small size
- No variants, same valve can perform all necessary tasks

Practical intermediate objectives could be:

- Response time is small compared to pressure wave propagation speed in the system. Propagation speed is usually below 1400 m/s or 1.4 m/ms, which means that response time of 0.1 ms could be considered as fast enough.
- Few percent gain variation may be acceptable if outer-loop feedback is used. It is not enough to have small absolute uncertainty but relative uncertainty must also be small.
- Durability must cover lifetime of the system.
- Valve variants for different number or ports and different flow ranges are allowed.

4.2 Is There Need for Perfect Valve?

A natural question is which the benefits of perfect valve are. If the price of the valve is low, the high performance does not matter. High performance allows new functions, such as:

- Active noise reduction
- Compensation for pump ripple
- Attenuation of pressure shock waves
- Emergency functions
- Bumbless transfer between different modes, such as inflow-outflow vs. differential mode or flow vs. pressure control mode.

The vision is that single high performance programmable valve allows *all* hydraulic functions of an actuator to be implemented with the same valve.

4.3 Miniaturization as a Method to Improve Digital Valves

Consider simple needle valve shown in *Figure 7*. Let assume that maximum needle lift x is proportional to diameter d, i.e. $x = Kd$. Assuming small opening ($K << 1$) and neglecting flow forces, the flow rate Q, closing force F and opening work W_{open} can be estimated as:

$$A = \pi x \sin\alpha \left(d - \frac{x}{2}\sin(2\alpha) \right) =$$
$$= d^2 K\pi \sin\alpha \left(1 - \frac{K}{2}\sin(2\alpha) \right)$$
$$Q = \mu A \sqrt{\frac{2(p_{in} - p_{out})}{\rho}} = d^2 K\pi\mu \sin\alpha \cdot$$
$$\cdot \left(1 - \frac{K}{2}\sin(2\alpha) \right) \sqrt{\frac{2(p_{in} - p_{out})}{\rho}} \qquad (2)$$
$$F = d^2 \pi (p_{in} - p_{out})/4$$
$$W_{open} \approx Fx = d^3 K\pi (p_{in} - p_{out})/4$$

These equations show that flow rate and closing force are proportional to square of diameter while opening work is proportional to cube of diameter. For example, if one valve is replaced with four smaller valves with half diameter, the result is same flow but halved opening work. The effect is even bigger in practice because smaller valve has lighter armature (mass is proportional to d^3) and because shorter actuation time is needed (lighter armature and shorter stroke). It can also be assumed that volume of valve is proportional to d^3. Thus, *replacing big valve with several smaller valves results in smaller total volume, faster response and smaller total switching energy.*

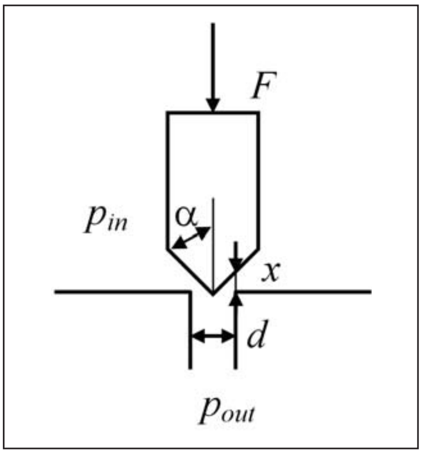


Figure 7. *Simple needle valve*

Although simplified calculations of a simple seat type valve are used, the benefits of miniaturization seem to be general. An example can be found in [2], in which characteristics of three highly optimized spool type on/off valves are presented. Volume of valve can be assumed proportional to spool travel and square of spool diameter, and flow rate is proportional to flow area. The data of [2] together with two efficiency numbers are presented in *Table 5*. Comparison show that switching time and relative power consumption decreases with decreasing size and that relative volume reduces or at least remains at the same level.

4.4 PNM-Coded Miniaturized Four-Way Digital Valve System

Analysis of Chapter 3 shows that PNM-coded digital valve systems give the best characteristics. Miniaturization also goes together well with PNM-coding because PNM calls for plurality of small valves. Let us assume that mass production makes on/

Table 5. *Comparison of three same type high performance on/off valves [2]*

Name	Spool diameter d [mm]	Spool travel x [mm]	Flow area A [mm^2]	Switching time [ms]	Switching energy W [J]	$\frac{A}{d^2x}$	$\frac{A}{W}$
Pilot	3	0.16	0.75	0.19	0.011	0.52	68
SI-1000	6.4	0.38	10	0.45	0.30	0.64	33
SI-1500	9.5	0.64	23	1.0	0.70	0.40	33

off valves so inexpensive that PNM-coded valve systems are feasible. A four-way PNM-coded digital valve system is next outlined. The target nominal flow rate is selected 100 l/min at 3.5 MPa per edge and the target flow resolution is 50:1. This requires 50 valves per edge or 200 valves in total. Each valve passes 2 l/min at 3.5 MPa, which means flow area of 0.6 mm^2. If pilot valve of Table 5 is used to implement this kind of valve package, its characteristics will be:

- Response time 0.2 ms independently on amplitude
- Nominal flow rate 100 l/min at Δp = 3.5 MPa per edge
- Flow resolution 50:1, actuator velocity resolution over 100:1 [18]
- Relative uncertainty of flow rate few percent
- Highly fault tolerant valve system
- Durability of each valve over 109 cycles [2]
- Programmable characteristics and possibility for differential connection [13]

Clearly this is towards perfect valve in terms of response time, uncertainty, reliability and programmability. Best existing analogue servovalves have several milliseconds response time from -100 to 100 percent and hardly any fault tolerance. The big number of valves is the biggest obstacle for implementation of this kind of valves, but mixed coding of Section 3.4 can be used to reduce number of valves.

5 Discussion and Conclusions

Analysis results of this paper show that digital valve systems based on parallel-connected on/off valves can provide unique features in terms of performance, accuracy and fault tolerance. Miniaturized PNM-coded digital valve systems have the best characteristics and there are no technical obstacles for implementation of 100 l/min valve (at Δp = 3.5 MPa) with 0.2 ms full-amplitude response time. High performance allows all hydraulic functions to be implemented with same type of digital valves, which allows huge reduction of the number of different valve variants. Vision is that only one type of on/off valve with some different sizes are mass-produced and assembled into some different programmable packages.

Essential question is can this kind of valve packages be produced in sufficiently low costs. The price of individual valve should be about 1 € in the four-way digital valve system of Section 4.4. It is clear that this can be achieved only in very big series. It is possible that completely different operation principles and manufacturing methods are needed. One possibility is valve matrix based on active materials, such as piezo [31]. Mixed coding seems an effective way to reduce the number of valves 50-70 percent. This requires bigger valves but may be feasible way to reduce price.

Miniaturization and corresponding increase of number of components seems to be effective method for improving characteristics of digital valves. Important questions, which are not studied in this paper, are how far miniaturization gives benefits and which the effects of miniaturization on valve actuator design are. It is clear that there is a limit for the degree of miniaturization because Reynolds number decreases as a result of miniaturization. The effects of miniaturization on valve actuator may be positive or negative. At least, the relative surface area increases, which helps to prevent overheating of actuator.

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Digitalna hidravlika – v smeri dovršene ventilske tehnologije

Razširjeni povzetek

Večina hidravličnih sistemov temelji na analognih krmilnih komponentah, kot so proporcionalni in servoventili ter črpalke z nastavljivo iztisnino, katerih veliki prednosti sta enostavnost in zveznost krmiljenja. Po drugi strani sta slabosti analognih komponent visoka cena in občutljivost na umazanijo, temperaturo in vibracije. Digitalna hidravlika predstavlja nedavno razvito alternativo tradicionalnemu krmiljenju s servo- ali proporcionalnimi ventili. Prednosti digitalne tehnologije so robustnost, ponovljivost in majhna napaka tolerance. Ključni princip digitalne ventilske tehnologije v hidravliki je uporaba več paralelno povezanih dvosmernih dvopoložajnih (on/off) ventilov v povezavi z inteligentnim krmiljenjem, kar zagotavlja redundantnost digitalnih hidravličnih sistemov.

V tem prispevku sta prikazana pregled in analiza različnih digitalnih ventilskih sistemov. Ventilski sistem z enako velikimi ventili je v mnogih pogledih optimalna rešitev. Izvedljivost in dosegljivost izvedbe tovrstnega pristopa krmiljenja sta v prispevku podrobneje pregledani in komentirani. Digitalna ventilska tehnologija predstavlja potencial za desetkrat hitrejši odziv, kot to omogočajo obstoječi ventili ob upoštevanju sprejemljive tolerance napake. Pri tem je miniaturizacija ventilov bistvena metoda v implementaciji tovrstnih ventilskih sistemov.

Analiza rezultatov tega članka potrjuje prednosti in implementacije digitalne ventilske tehnologije ob uporabi velikega števila istega tipa ventila, kar omogoča znatno zmanjšanje različnih variant uporabljenih ventilov. Končni cilj je velikoserijska izdelava enega samega tipa dvopoložajnega ventila z nekaterimi različnimi velikostmi in kombiniranje teh ventilov v različne programabilne pakete. Pri vsem tem je ključno vprašanje, ali lahko takšni programabilni ventilski paketi dosežejo dovolj nizko tržno ceno. To je možno doseči le v dovolj velikih proizvodnih serijah, pri tem pa lahko nastopijo tudi možnosti popolnoma drugačnih principov delovanja in proizvodnih metod ventilov.

Ob vsem tem pa ostajajo odprta vprašanja, v kolikšni meri lahko miniaturizacija pozitivno prispeva in kakšni so učinki miniaturizacije na konstrukcijo in obliko samega aktuatorja ventila.

Izvleček: Digitalna hidravlika predstavlja nedavno razvito alternativo tradicionalnemu krmiljenju s servo- ali proporcionalnimi ventili. Ključni princip je uporaba paralelno povezanih dvosmernih dvopoložajnih (on/off) ventilov v povezavi z inteligentnim krmiljenjem. V tem prispevku sta prikazana pregled in analiza različnih digitalnih ventilskih sistemov. Ventilski sistem z enako velikimi ventili je v mnogih pogledih optimalna rešitev. Izvedljivost in dosegljivost izvedbe tovrstnega pristopa krmiljenja sta v prispevku podrobneje pregledani in komentirani. Digitalna ventilska tehnologija je potencial za desetkrat hitrejši odziv, kot to omogočajo obstoječi ventili ob upoštevanju sprejemljive tolerance napake. Miniaturizacija ventilov pa je bistvena metoda v implementaciji tovrstnih ventilskih sistemov.

Ključne besede: digitalna hidravlika, digitalno krmiljenje, miniaturizacija,