Fundamentals of Digital Microhydraulics

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Abstract

Digital hydraulic valve systems have been studied much during the last decade. Typical approach is to use 4-9 on/off valves in parallel and to adjust the volume flows of the valves according to powers of two. This paper discusses an alternative approach in which a big number of miniaturized on/off valves are used. Analysis show that the approach have a lot of benefits. The main challenge is the requirement for small and low-cost on/off valves.

KEYWORDS: digital hydraulic valve systems, PNM coding, miniaturization

1. Introduction

Digital fluid power is a new and rapidly developing fluid power area. Two main approaches are switching systems and systems based on parallel connected valves /1, 2/. The latter one has been studied at the Tampere University of technology since 2000. The main efforts have been model-based control /3/, fault tolerance /4/, energy efficient control /5/, and reduction of pressure pulsation /6/. Direct operated commercial solenoid valves have been used with in-house designed booster electronics, which gives the valve response time of 8-15 ms. Even these relatively slow response valves have been used successfully in demanding servo applications /7, 8/.

The basic unit of the parallel connected valve system is digital flow control unit (DFCU), which consists of a number of parallel connected valves. **Figure 1 (a)** shows an example of DFCU and its simplified drawing symbol. The relative flow capacities of valves are usually adjusted according to powers of two, i.e. 1:2:4:8:16 etc., which is known as binary coding. The practical implementation is to use identical valves and to install orifice with suitable flow area after the valve. The typical number of parallel connected valves is between five and nine /5, 7, 9/. The four-way valve is implemented by four DFCUs as shown in Figure 1 (b), and 4×5 valves is typical solution. Sufficient resolution is achieved by utilizing small cross flow /3/. This configuration gives same functionality than conventional distributed valve systems /10, 11/. The benefits of the digital solution are that bi-directional valves are available and that exact timing of valves allows switching of the control mode during the motion /5/.

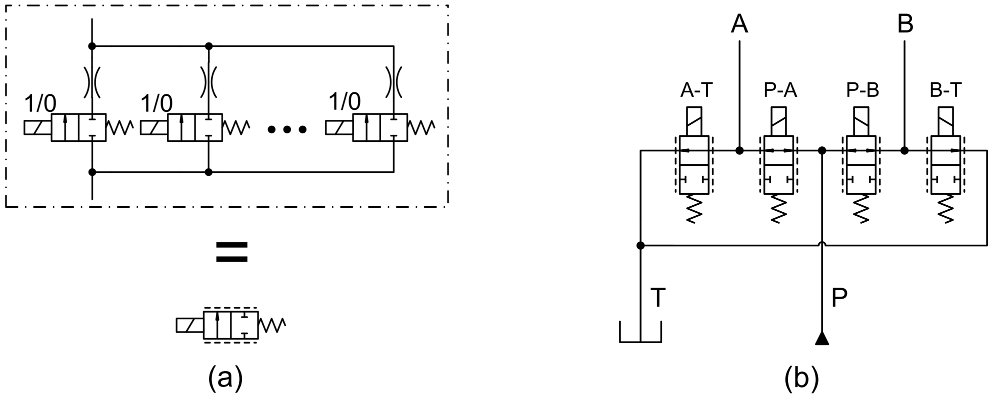

Figure 1. Digital flow control unit (DFCU) and its simplified drawing symbol (a). Digital hydraulic four-way valve (b).

Binary coded DFCU has challenges, such risk for pressure transients, unequal valve characteristics, moderate fault tolerance and relatively slow response. Fault tolerance is unique feature of the DFCU but fault in the bigger valves degrade the performance significantly in the binary coded system /4/. Pressure transients cannot be avoided in binary coded systems with uncertainty in the delays of the valves /6/. Very fast valves are needed in the implementation of the pressure relief function, for example /12/.

This paper analyses a solution based on hundreds of miniaturized parallel connected valves, so called digital microhydraulics. The principle and some characteristics have been presented in /13/. The research after that has been concentrated on the development of suitable valves /14, 15/. This paper gives the motivation for digital microhydraulics, analyses its characteristics, discusses about the requirements for valves, and presents some control principles. The deeper analysis of the solenoid actuator is made and results show that the assumptions regarding the size of the valve in /13/ are too optimistic.

2. PNM Coded DFCU – Heart of Digital Microhydraulics

Pulse Number Modulation (PNM) coding means that each valve of the DFCU has the same flow capacity. The flow rate of the DFCU is controlled by the *number* of open valves instead of the *combination* of open valves. The change of coding method affects significantly the characteristics of the DFCU and the main differences are discussed in this chapter.

2.1. Resolution and Number of Valves

The number of output values is M+1 in the PNM coded DFCU instead of 2^M of the binary coded one, where M is the number of parallel connected valves. Therefore, much more valves are needed in order to achieve the same number of output values. The resolution of 61:1 is achieved by 6 valves with binary coding while 61 valves are needed with PNM coding, for example.

2.2. Fault Tolerance

The binary coded DFCU is fault tolerant and faults can be compensated in many cases with slightly reduced performance. The number of possible output values halves if one valve does not work. The “valve does not open” fault is easier to compensate for and the effect of this kind of fault in different valves is shown in **Figure 2**. Fault in the biggest valve halves the maximum flow but do not change the step size while the fault in the smallest valve is just opposite. Fault in the middle valves cause big steps in the output values. The similar fault map for some faults in the PNM coded DFCU is depicted also in Figure 2. Any single valve fault in the PNM coded DFCU removes only one output value and has hardly any effect on the controllability. The “valve jammed open” fault can be disastrous in the binary coded DFCU. If the biggest valve jams open, the opening of the DFCU is 50 % and the system is probably in the uncontrollable state. Similar fault in the PNM coded DFCU causes tiny leakage, which is not dangerous situation, but may hamper the operator or controller.

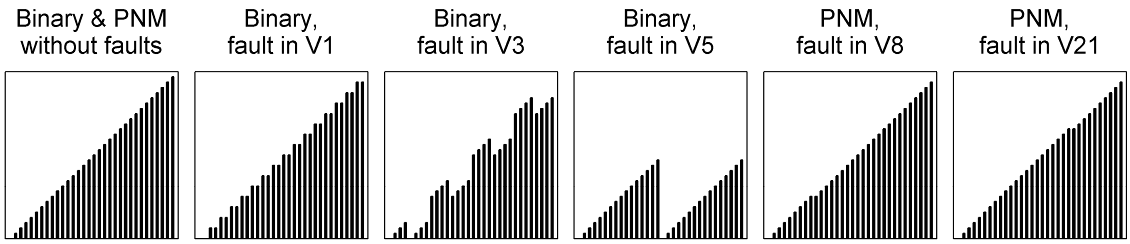

Figure 2. The effect of the ”valve jams closed” type fault on the characteristics of the 5-bit binary coded and 31-bit PNM coded DFCU.

2.3. Pressure Transients

The origin of pressure transients in the binary coded DFCU is the fact that simultaneous opening of some valves and closing of the others is needed. The extreme situation occurs in the state transition, in which the largest valve is opened and the others are closed at the same time or vice versa. If the delays of valves vary, the DFCU can be fully open or fully closed for a moment yielding big pressure transient. This phenomenon has been detected more or less in practically all systems implemented so far. The simultaneous opening and closing of valves is never needed in the PNM coded DFCU because the opening is controlled by the number of open valves. This means that pressure transients caused by DFCU state transitions are small or negligible.

2.4. Fast and Predictable Response Time

All valves are small and similar in PNM coded DFCU. The response times are generally smaller in small valves as shown in the next chapter. Because all valves are similar, the variation in the response times is small. The possible non-symmetry in opening and closing delays is not a problem because of the operation principle.

2.5. Equal loading for valves

One problem of the binary coded DFCU is that the smallest valve is much more active than the bigger ones. The problem does not exist in the PNM coded DFCU because valves are similar and can be used by turns.

2.6. Summary

If the binary coded DFCU is replaced by the PNM coded one with big number of small valves, practically all control challenges of the digital hydraulic valve systems disappear. The approach yields fast and highly fault tolerant valve systems without significant pressure transients. The problem of the approach is the big number of valves needed.

3. Theoretical Characteristics Of Miniaturized Valve Systems

3.1. Scaling of Actuator and Flow Passage

This chapter analyses, what happens on the valve characteristics when its size is scaled. Essential parameter is the flow density of the valve, i.e. the area of the flow path divided by the volume of the valve. If the flow density is independent on the real size of the valve, the size of the DFCU remains the same even if the number of valves is increased. The analysis of this chapter assumes that direct operated valve with solenoid actuator is used. **Figure 3** presents the sketch of the valve studied. Two scaling variables are used: The solenoid dimensions are proportional to the solenoid diameter d_s while the dimensions of the flow passage are proportional to orifice diameter d_h. The air gap of the solenoid g is proportional to d_h because this selection guarantees that the geometry of the flow passage is independent on d_h. The size of the valve is in practice determined by the size of the solenoid and following results are obtained from Fig. 3:

1. Mass and volume of the armature, actuator and valve ~ d_s^3
2. Area of the flow path and flow rate ~ d_h^2 (turbulent flow is assumed)
3. Pressure force ~ d_h^2

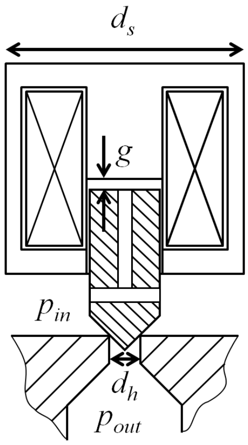

Figure 3. Sketch of the direct operated needle valve.

3.2. Solenoid Actuator

A rough approximation for the solenoid force is /16/:

$$F_s = \frac{\mu_0 (NI)^2 A}{2g^2} \tag{1}$$

where μ_0 is the vacuum permeability, N the number of turns, I the current, A the area of the air gap and g the height of the air gap. If the current density is constant, the term NI is proportional to d_s^2. Now A is proportional to d_s^2 and g is proportional to d_h, which gives:

$$F_s \sim d_s^6 d_h^{-2} \tag{2}$$

3.3. Scaling of Valve

The scaling is made as follows:

$$d_s \sim d_h^{2/3} \tag{3}$$

Subsituting this into Eq. 2 gives that solenoid force is proportional to d_h^2. Because the pressure force is also proportional to d_h^2, the selection of Eq. 3 guarantees that the solenoid is capable to open the valve after scaling. This of course assumes that Eq. 1 is valid for any size of solenoid. Deeper analysis is needed to find out what happens in practice.

3.4. Flow Density

The consequence of Eq. 3 is that the volume and mass of the valve are proportional to d_h^2. The orifice area is proportional to d_h^2 and the flow density is thus independent on scaling. This means that the size of DFCU is independent on the number of valves if the flow capacity is kept the same. The PNM coded DFCU may be even smaller, because there is no need to install orifices after valves like in binary coded DFCU.

3.5. Response Time and Opening Energy

The response time of the valve depend on the actuator, spring, and pressure forces as well as mass and travel of the armature. Considering the closing of the valve without spring and flow forces gives armature acceleration independent on d_h (both pressure force and armature mass ~ d_h^2). Because lift is proportional to d_h, the closing time is proportional to $d_h^{1/2}$. The situation is the same in the opening because the solenoid force is proportional to d^2. Thus, the response time should be smaller for smaller valves, which is intuitive. It must be noted that the response time depends also strongly on the coil inductance and control electronics.

The relative opening energy of the valve is defined as the opening work divided by the flow area. The opening work is the product of pressure force and armature lift and thus proportional to d^3. The result is that the relative opening energy is proportional to d.

3.6. Summary

The simplified analysis show that miniaturization of the valve should have positive effect on its main characteristics. Response time and relative opening energy decreases, while the flow density remains approximately the same. The analysis thus gives motivation for the miniaturization.

4. Valves for Digital Microhydraulics

4.1. Valve Requirements

The most important requirement for the miniaturized valve is that it is inexpensive in the mass production. This means simple construction, loose tolerances and preferably one moving part only. Another key requirement is the physical size and possibility to pack valves compactly. Switching energy, peak current and hold power must also be small enough in order to avoid expensive control electronics and too big electric power consumption. Response time should be 2 ms or less in order to be applicable in all applications /12/. Bi-directional flow is preferred, because it allows the implementation of different control modes, such as regenerative connection.

4.2. Flow Rate of Valve

Typical flow rate of hydraulic valves is 20-200 l/min at Δp = 0.5 MPa. The lower limit for the individual valve of the DFCU is obtained by assuming high resolution and small flow rate. The requirements of resolution of 100:1 and together with maximum flow rate of 20 l/min at Δp = 0.5 MPa at yields flow rate of 0.2 l/min per valve at Δp = 0.5 MPa. The corresponding orifice diameter is about 0.43 mm, which probably cannot be used without pre-screen. If only one valve size is used, a reasonable orifice size could be 0.8 mm corresponding to flow rate of 0.7 l/min at Δp = 0.5 MPa. The number of valves could then be 30-300 per DFCU.

4.3. Size of Valve and Valve Package

The valve package based on digital microhydraulics principle should not be bigger than traditional valve. Bosch Rexroth NS6 high response proportional valve is taken as the reference /17/. Its dimensions are 200 x 132 x 46 mm (l x h x w), and flow rate is 40 l/min at Δp = 3.5 MPa. The NS6 interface takes 70 mm from the length and there is thus 130 mm available for the miniaturized valves. If the diameter of the miniaturized valve is 10 mm and height 40 mm, it is possible to pack 4 x 20 valves into the space of the reference valve. The suggestive design is shown in **Figure 4**. The length of the traditional valve is not the most critical parameter and valves with length of 260 mm exist, for example. If this is allowed, the number of valves increases to 4 x 32, which is already in the design range. It can be concluded that the maximum valve diameter is 10 mm, if the design of Fig. 4 is used.

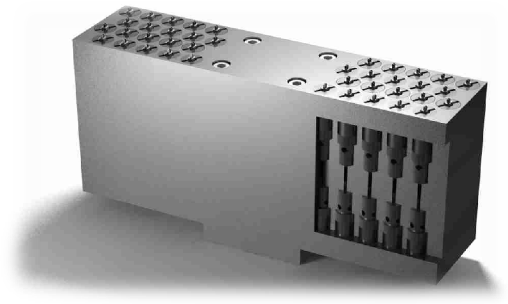

Figure 4. Suggestive design for 4x20 microhydraulic valve package with NS6 interface. The size of the valve package is 200 x 100 x 46 mm.

4.4. Suitability of Existing Valves and Valve Prototypes

4.4.1. Lee Piloting Valve

The Lee Company produces small direct and pilot operated seat type on/off valves /18/. The direct operated valve has equivalent orifice diameter of approx. 0.53 mm, and the response time is 15-35 ms. The physical size is about ϕ23 mm x 42 mm giving flow density of 0.013 m^{-1}. The corresponding values for the pilot operated version are equivalent orifice diameter 1.55 mm, response time 30 ms maximum, size ϕ28 mm x 49 mm and flow density of 0.063 m^{-1}. Both the physical size and response time are unsuitable for digital microhydraulics.

4.4.2. Sturman Pilot Valve

The Sturman pilot valve is ultra fast bistable direct operated spool type valve /19/. The equivalent orifice diameter is about 1 mm, response time is 0.19 ms and switching energy is 11 mJ. It is difficult to determine the size of the valve but it seems to be about 10 x 10 x 26 mm according to the figure given in the reference. The estimate for the flow density is thus 0.30 m^{-1}. The manufacturing cost is 10 $ in the mass production according to the manufacturer. The valve seems to be suitable for the digital microhydraulics and the only problems are too high price and leakage caused by the spool design. The possibility for bi-directional flow is not known.

4.4.3. Prototype of Direct Operated Needle Valve

The approach used in /14, 15/ is to design as simple as possible direct operated needle valve with highly optimized design. Special attention is paid on the optimization of the solenoid actuator, especially its diameter. The latest prototype /15/ has 0.7 mm orifice and size of ϕ11 x 39 mm yielding to flow density of 0.10 m^{-1}. The opening time is 2-4 ms, switching energy is 77 mJ and hold power is 81 mW only. The closing time is 3 ms at higher pressure differentials but increases rapidly at smaller pressure differentials. The design is simple and leak free but allows unidirectional flow only.

4.5. Summary

The conclusion is that requirements for the valves of digital microhydraulics are demanding. The Sturman pilot valve mostly fulfils the requirements but may be too expensive. The needle valve prototype is zero leak and probably cheaper, but its flow density is not so good. Bi-directional solutions do not exist, which hamper the full utilization of digital valve systems.

5. Control Methods for Digital Microhydraulics

The PNM coded DFCU has several control advantages when compared to the binary coded one. The reason for this is that the output is controlled by the number of open valves instead of the opening combination. Two benefits are discussed in this chapter: faster response time and possibility for equal duty of valves.

5.1. Improved Response Speed

To simplify the text, “valve delay” means here the maximum of the closing and opening delays of all valves of the DFCU. The deterministic valve behaviour requires that valve control signal do not change too often. The valve delay is considered as a minimum period, although slightly longer period is normally used. The control rules are:

1. Valve can be commanded ON, if its command signal has been OFF at least the duration of the valve delay.
2. Valve can be commanded OFF, if its command signal has been ON at least the duration of the valve delay.

These rules are strict for the binary coded DFCU. Even if only one valve changes its state, there is 50 % probability that the same valve must change its state in the next state transition. The normal implementation is thus to use fixed sampling period slightly longer than valve delay. The conditions 1 and 2 above are much easier to meet with PNM coding. Consider a PNM coded DFCU with 4 valves. A ramp response example is shown in **Figure 5**. It is assumed that the reference signal updates with 2 ms sampling interval and that the duration between control signals of the each valve is at least 7 ms. The valve delay is assumed to be 5 ms and opening time 1 ms. The figure shows that the PNM coded DFCU follows accurately the reference signal after the delay. The response of the binary coded DFCU is also shown. The follow-up is poor and slower than with PNM coding because the output update interval is 7 ms only (update at *t* = 7 ms, *t* = 14 ms etc.). It can be concluded that PNM coded DFCU is faster and follows the reference more accurately.

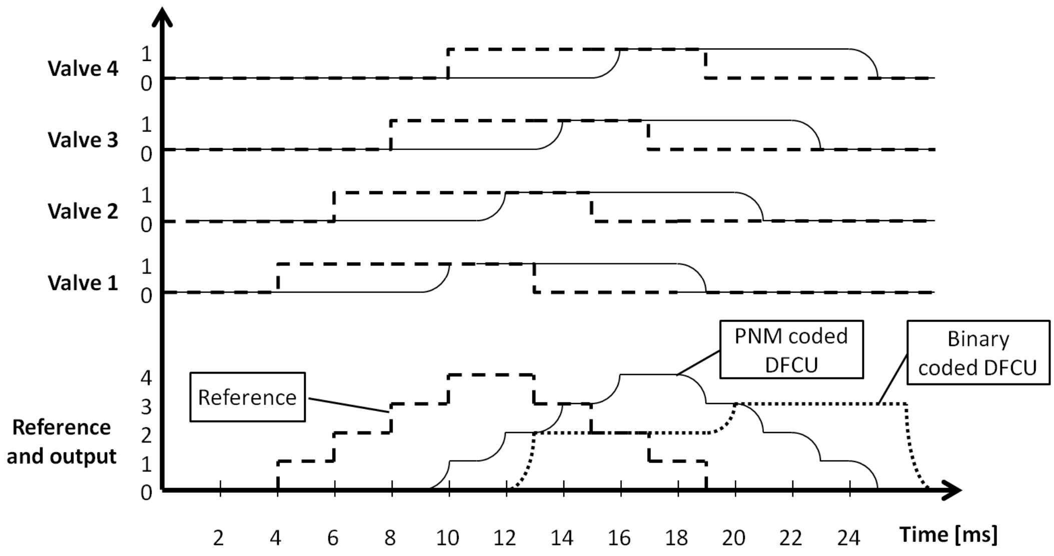

Figure 5. A ramp response of the PNM and binary coded DFCUs. Valve delay is 5 ms and opening time is 1 ms. The minimum duration between controls is 7 ms.

5.2. Equalizing Duty of Valves

A simple way to implement equal load for individual valves is the “snake game” approach. The principle is shown in **Figure 6**. The switching order of valves is determined first. The opening of valves is implemented at the “head” of the switching trail and the closing is implemented at the “tail” end. The approach maximises the probability that there are valves available also with fast reference changes. Those valves, which have been closed for the longest time, are opened and vice versa.

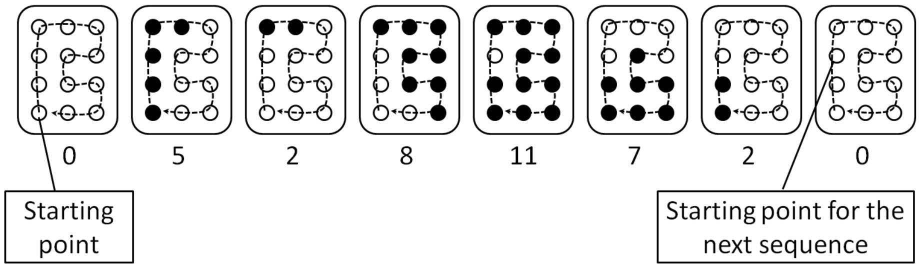

Figure 6. Example of control sequence for a 12 bit PNM coded DFCU.

6. Conclusions

The principle of “Digital Microhydraulics” approach is to use a big number of parallel connected miniaturized on/off valves for implementing hydraulic valve functions. The analysis results of this paper predict improved characteristics when compared to the traditional binary coded digital valve systems. Improved fault tolerance, response speed and pressure behaviour are the main benefits. The approach should not have negative effect on the size of the valve package. The only drawback of the approach is that big number of valves is needed, typically over 30 per DFCU and over 120 for the complete four-way valve implementation. This calls for small, simple and low-cost valves. The analysis of the existing valves and valve prototypes show that the valve technology should be solvable challenge, but highly optimized multidisciplinary design of the valve and manifold is needed.

Is digital microhydraulics the correct direction in the development of hydraulic valves? The experiences with the existing binary coded digital valve systems are encouraging and the characteristics of the microhydraulic valve systems are much better. Everyone wants to have big number of pixels in their digital camera. Why not in digital hydraulic valve packs?

7. Acknowledgement

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8. References

/1/ Scheidl, R. 2008. Hydraulic Switching Control - Principles and State of the Art. **In:** Linjama, M. & Laamanen, A. (eds.). The First Workshop on Digital Fluid Power, October 3, 2008, Tampere, Finland, pp. 31-49.

/2/ Linjama, M. 2011. Digital fluid power - state of the art. **In:** Sairiala, H, & Koskinen, K. (eds.). Proceedings of the Twelfth Scandinavian International Conference on Fluid Power, SICFP'11, May 18-20, 2011, Tampere, Finland, pp. 331-354 (Vol. 3).

/3/ Linjama, M. & Vilenius, M. 2005. Improved Digital Hydraulic Tracking Control of Water Hydraulic Cylinder Drive. International Journal of Fluid Power, Vol. 6, No. 1, pp. 29-39.

/4/ Siivonen, L., Linjama, M., Huova, M. & Vilenius, M. 2009. Jammed On/Off Valve Fault Compensation with Distributed Digital Valve System. International Journal of Fluid Power, Vol. 10, No. 2, pp. 73-82.

/5/ Huova, M., Karvonen, M., Ahola, V., Linjama, M. & Vilenius, M. 2010. Energy Efficient Control of Multiactuator Digital Hydraulic Mobile Machine. 7th International Fluid Power Conference, March 22-24, 2010, Aachen, Germany, pp. 25-36 (Vol. 1).

/6/ Laamanen, A. 2009. Minimization of State Transition Uncertainty in the Digital Valve System. Dissertation thesis. Tampere University of Technology. Publication 809. 111 p.

/7/ Hopponen, V., Linjama, M., Ikonen, A., Rintamäki, P., Pietola, M. & Vilenius, M. 2009. Energy Efficient Digital Hydraulic Force Control. The 11th Scandinavian International Conference on Fluid Power SICFP'09, June 2-4 2009, Linköping, Sweden, 11 p.

/8/ Linjama, M., Seppälä, J., Mattila, J. & Vilenius, M. 2008. Comparison of Digital Hydraulic and Traditional Servo System in Demanding Water Hydraulic Tracking Control. **In:** Johnston, D.N. & Plummer, A.R. (eds.). Fluid Power and Motion Control (FPMC 2008) Centre for Power Transmission and Motion Control University of Bath, UK, pp. 393-403.

/9/ Siivonen, L., Linjama, M., Vilenius, M. & Anttonen, P. 2008. Accurate flow control with digital valve system. Proceedings of the 51st National Conference on Fluid Power, March 12-14, 2008, Las Vegas, USA, pp. 287-294.

/10/ Shenouda, A. & Book, W. J. 2005. Selection of Operating Modes of a Multi-Functional Hydraulic Device. 2005 ASME International Mechanical Engineering Congress and Exposition, Nov. 5–11, Orlando, Florida, USA, 11 p.

/11/ Pfaff, J. 2005. Distributed Electro-Hydraulic Systems for Telehandlers. The 50th National Conference on Fluid Power, March 16-18, 2005, Las Vegas, USA. pp. 779–784.

/12/ Ketonen, M. 2011. Digitaalihydraulisen Paineenrajoitustoiminnon Suunnittelu ja Toteutus. M.Sc. Thesis, Tampere University of Technology, 80 p. (In Finnish)

/13/ Linjama, M. & Karvonen, M. 2008. Digital Microhydraulics. **In:** Linjama, M. & Laamanen, A. (eds.). Proceedings of the First Workshop on Digital Fluid Power 3rd October, 2008, Tampere, Finland, pp. 141-152.

/14/ Karvonen, M., Juhola, M., Ahola, V. Söderlund, L. & Linjama, M. 2010. A miniature needle valve. **In:** Laamanen A. & Linjama M. (eds.). Proceedings of the Third Workshop on Digital Fluid Power, October 13-14, 2010, Tampere, Finland , pp. 61-78.

/15/ Puumala, V. 2012. Nopea Neulaventtiili Digitaalihydrauliikkaan. M.Sc. Thesis, Tampere University of Technology (In Finnish, to be published)

/16/ Sadiku, M. 1995. Elements of Electromagnetics, second edition. Oxford University Press, NY, 821 p.

/17/ Anon. High-Response Valve with Integrated Digital Axis Controller (IAC-R) and Field Bus Interface. Bosch Rexroth technical brochure RE29191/09.10, 22 p.

/18/ Anon. 2009. Technical Hydraulic Handbook, eleventh edition. The Lee Company, USA, 691 p.

/19/ Johnson, B., Massey, S. & Sturman, O. 2001. Sturman Digital Latching Valve. **In:** Palmberg, J.-O. (ed.). The Seventh Scandinavian International Conference on Fluid Power, SICFP'01, pp. 299–314 (Vol. 3)